

THE ROTHAMSTED MONOGRAPHS ON

AGRICULTURAL SCIENCE

EDITED BY

DR. E. J. RUSSELL, D.Sc. (LOND.), F.R.S.

SOIL CONDITIONS AND PLANT GROWTH

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DURING the past ten years there have been marked developments in knowledge of the relations between the soil and the growing plant. The subject involves physical, biological, and chemical considerations, and its ramifications are now so wide that they cannot be satisfactorily dealt with in detail in any one book. These monographs collectively cover the whole ground. In "Soil Conditions and Plant Growth" the general outlines are presented: in the monographs the various divisions are fully and critically dealt with by the Heads of the Departments concerned at Rothamsted. A homogeneous treatment is thus secured that will, it is hoped, much facilitate the use of the series.

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By EDWARD J. RUSSELL, D.Sc. (LOND.), F.R.S.

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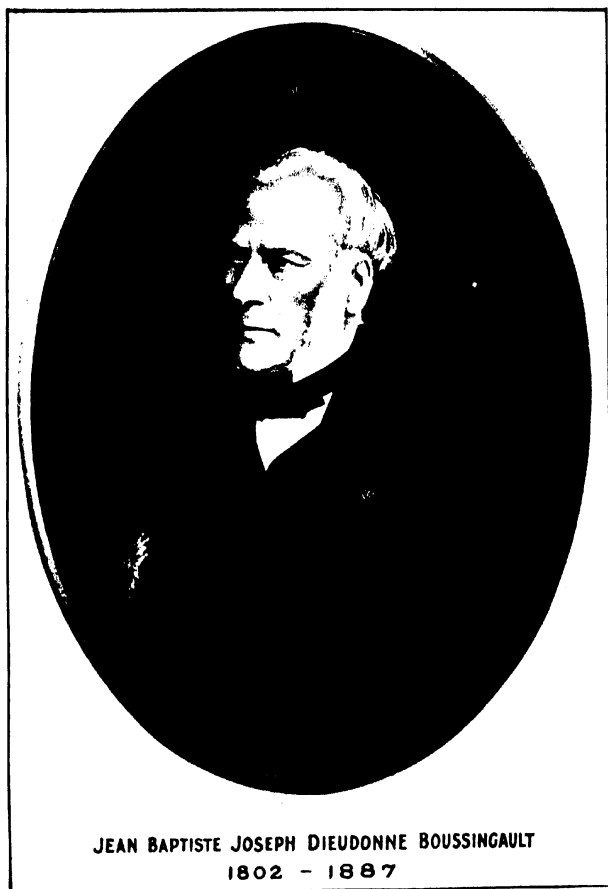
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SOIL CONDITIONS

AND

PLANT GROWTH

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SOIL CONDITIONS

AND

PLANT GROWTH

BY
EDWARD J. RUSSELL, D.Sc. (LOND.), F.R.S.
DIRECTOR OF THE ROTHAMSTED EXPERIMENTAL STATION, HARPENDEN

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39 PATERNOSTER ROW, LONDON
FOURTH AVENUE & 30TH STREET, NEW YORK
BOMBAY, CALCUTTA, AND MADRAS
1921

BIBLIOGRAPHICAL NOTE.

| | | |
|--|-----------|------|
| First Edition (in Monographs on Biochemistry) | June, | 1912 |
| New Impression | April, | 1913 |
| New Edition | February, | 1915 |
| Third Edition | June, | 1917 |
| Fourth Edition (in Rothamsted Monographs on Agricultural Science) | July, | 1921 |

PREFACE TO THE FOURTH EDITION.

WHEN the revision of the present edition was begun it became obvious that some fundamental change would be necessary in the treatment. Since the first edition was published in June, 1912, the subject has grown enormously : it has now completely run away from the 166 pages that proved a sufficient allowance in those days. Several courses were open ; the one chosen was to retain the general characteristics of the older editions, dealing broadly with the whole subject, emphasising the outlines and endeavouring to maintain a dispassionate balance between the various parts. Detailed treatment has been avoided, partly because it is now hopeless for any one individual to attempt it, and partly because I did not wish to overload the book and make it into a huge " Handbuch " where the outlines are all obscured and the perspective lost.

At the same time, however, the student must have access to the more detailed treatment, and it would have helped him little had I simply published a card index and left him to find out the rest for himself.

The problem was solved by enlisting the sympathy of the Heads of the Departments at Rothamsted, who each undertook to write a monograph dealing with his or her special branch, and which Messrs. Longmans will publish uniformly with this volume. Each one has discussed with me the corresponding sections of this

book, with the results that the book is much improved and a definite continuity is assured between this general monograph and the detailed monographs to which it will serve as a link. The whole series is to be called "The Rothamsted Monographs on Agricultural Science."

It is hoped that this new arrangement will prove satisfactory to students. It has the advantage that the book still covers the whole ground, while remaining of a manageable size, and that it is closely linked up with a series of similar books, each dealing with separate sections, in which more complete treatment and more fully informed criticism are given than I could myself undertake.

On the other hand, the necessity for freedom of treatment, and the difficulty of placing such subjects as Soil Physics or Soil Protozoa under the heading of Biochemistry, compelled the withdrawal of the book from the important "Biochemical Series," of which it has hitherto been a member. And, although Drs. Plimmer and Hopkins willingly consented, this course was not taken without serious consideration and regret: it involves the separation of the book from a very useful series of volumes.

Perhaps the most striking feature of the past ten years' developments has been the increasing recognition of the complexity of soil phenomena. The American investigations have shown how complex are the physico-chemical relations of the soil, the soil solution and the plant. English work has shown that the soil population is numerous and very varied. It is not sufficiently recognised, however, that this complexity necessitates a difference in method of investigation from that usually adopted in scientific laboratories, and this I have tried to bring out in the course of the book. A chemist

dealing with a single substance can treat it in a certain way, and be reasonably certain that the result obtained is the direct consequence of the treatment. The soil investigator has no such certainty: definite treatment of a soil may be followed by a definite result, but there may be no direct relationship with the factor under investigation—the result may be merely a reflex of some far-reaching change produced in some other factor which is entirely overlooked. Further, if observations are attempted in the field it is impossible to ensure such simple variation as the recorded data seem to suggest. It follows that the ordinary laboratory method in which factors are varied only one at the time requires considerable modification when used for soil work.

The methods in use at Rothamsted fall into two groups:—

1. Observations are made in natural conditions as accurately as is feasible, and repeated sufficiently frequently to allow of treatment by modern statistical methods. These enable the investigator to study the variations, and hence to make deductions as to the numbers and properties of the factors involved. The factors can then be studied in the laboratory as single factors, using more precise methods and more rigid controls than are possible in the field.

2. Experiments are made on the soil, and from the results deductions are drawn as to the probable nature of some new factor. Direct experiment is then made to test the operation of the factor in the field, and precise laboratory experiments are also undertaken.

Further, just as the ordinary methods of investigation are insufficient, so also the customary divisions of science cannot be rigidly maintained in soil work. The chemist is constantly confronted with physical and biological

problems: the biologist constantly needs the help of the statistician, the physiologist and chemist: most of the work is essentially "team work," requiring close co-operation between experts in different branches of science.

The recognition of these considerations, and the fact that the Ministry of Agriculture has now, through the Development Fund, enabled Rothamsted to interest some of the more promising of the younger scientific workers in agricultural problems, justifies the hope that the future will see even greater advances than the past.

In preparing this edition thanks are due to my colleagues at Rothamsted who have read sections or chapters of the book and made useful comments, especially to Miss Aslin, Dr. B. Muriel Bristol, Miss Jewson, Messrs. W. B. Brierley, D. W. Cutler, E. M. Crowther, B. A. Keen, and H. J. Page; to Professor V. H. Blackman, Mr. G. W. Robinson, of University College, Bangor, and Dr. E. J. Salisbury; to M. Georges Matisse, of Paris, who is translating this edition into French; and in America to Dr. H. L. Walster for a valuable critical review and list of references, and others for useful suggestions. The book has been helped by so many that I hope it will still find friends in spite of its larger size.

PREFACE TO THE THIRD EDITION.

CONSIDERABLE alterations have been made in the text and a new chapter has been added discussing the colloidal properties of the soil. It is abundantly clear that the soil investigator of the future will have to be thoroughly familiar with the ways of colloids, and I fully expect that much of the older work will require careful re-examination in the light of what has been done in this direction by chemists and physicists.

Although the volume has necessarily expanded I have tried to keep it as a monograph: I have not attempted to turn it into an extended card index by referring to every paper published on the subject since the first edition came out. Many papers have been omitted; the guiding principle has been to include only those that brought in some new idea or profoundly modified an old one. Some of the papers omitted from the last edition have been included in this because they now fall into their place, while before they did not. Doubtless this will happen again.

Continued progress is being made. Since the book was first begun two Journals have sprung up devoted entirely to soil: *Soil Science*, under the editorship of the indefatigable J. G. Lipman, and the *International Mitteilungen für Bodenkunde*. Another Journal, the *Journal of Ecology*, has also arisen and is vigorously developing another aspect of the same subject, while the older agricultural journals are finding more and more of their space taken up by soil papers. The subject now only lacks a name, and though many have been proposed—pedology, agrogeology, edaphology, etc.—I have not felt drawn to any of them.

CONTENTS.

| CHAPTER | PAGE |
|---|------|
| I. HISTORICAL AND INTRODUCTORY - - - - | 1 |
| II. SOIL CONDITIONS AFFECTING PLANT GROWTH - - | 30 |
| III. THE COMPOSITION OF THE SOIL - - - - | 92 |
| IV. THE COLLOIDAL PROPERTIES OF SOIL - - - | 148 |
| V. THE CARBON AND NITROGEN CYCLES IN THE SOIL - | 175 |
| VI. THE BIOLOGICAL CONDITIONS IN THE SOIL - - | 218 |
| VII. THE MICRO-ORGANIC POPULATION OF THE SOIL AND ITS RELATION TO THE GROWTH OF PLANTS - | 250 |
| VIII. THE SOIL IN RELATION TO PLANT GROWTH - - | 301 |
| IX. SOIL ANALYSIS AND ITS INTERPRETATION - - - | 322 |

APPENDICES.

| | |
|--|-----|
| I. THE METHODS OF SOIL ANALYSIS - - - - | 347 |
| II. AMOUNTS OF VARIOUS SUBSTANCES ABSORBED FROM THE SOIL BY THE COMMON AGRICULTURAL CROPS OF ENGLAND - - - - | 357 |
| III. A SELECTED BIBLIOGRAPHY OF PAPERS ON SOIL CON- DITIONS AND PLANT GROWTH - - - - | 359 |
| AUTHOR INDEX - - - - - | 387 |
| SUBJECT INDEX - - - - - | 395 |

LIST OF PLATES.

PORTRAIT OF J. B. J. DIEUDONNÉ BOUSSINGAULT (1802-
 1887) - - - - - - - *Frontispiece*

TO FACE PAGE

FIG. 9.—INFLUENCE OF MEDIUM ON ROOT DEVELOPMENT OF
 LUPINES - - - - - - - - - 53

FIG. 11.—SWEDES FROM AGDELL FIELD, BROADBALK: UN-
 MANURED; SUPERPHOSPHATES AND POTASSIC FERTILISERS;
 AND COMPLETE FERTILISER - - - - - - 65

| | |
|---|------------------|
| FIG. 30A.—POOR GRASS PASTURE, UNTREATED PLOT, HORNDON-ON-THE-HILL, ESSEX (LONDON CLAY) - | } <i>between</i> |
| FIG. 30B.—ADJOINING PLOT, BUT TREATED WITH GAFSA PHOSPHATE, FEB. 27TH, 1918 - - | } 312 & 313 |

CHAPTER I.

HISTORICAL AND INTRODUCTORY.

IN all ages the growth of plants has interested thoughtful men. The mystery of the change of an apparently lifeless seed to a vigorous growing plant never loses its freshness, and constitutes, indeed, no small part of the charm of gardening. The economic problems are of vital importance, and become more and more urgent as time goes on and populations increase and their needs become more complex.

There was an extensive literature on agriculture in Roman times which maintained a pre-eminent position until comparatively recently. In this we find collected many of the facts which it has subsequently been the business of agricultural chemists to classify and explain. The Roman literature was collected and condensed into one volume about the year 1240 by a senator of Bologna, Petrus Crescentius, whose book¹ was one of the most popular treatises on agriculture of any time, being frequently copied, and in the early days of printing, passing through many editions—some of them very handsome, and ultimately giving rise to the large standard European treatises of the sixteenth and seventeenth centuries. Many other agricultural books appeared in the fifteenth and early sixteenth centuries, notably in Italy, and later in France. In some of these are found certain ingenious speculations that have been justified by later work. Such, for instance, is Balissy's remarkable statement in 1563 (222)²: "You will admit that when you bring dung into the field it is to return to the soil something that has been taken away. . . . When a

¹ *De agricultura vulgare*, Augsburg, 1471, and many subsequent editions.

² The numbers in brackets refer to the Bibliography at the end of the book.

plant is burned it is reduced to a salty ash called alcaly by apothecaries and philosophers. . . . Every sort of plant without exception contains some kind of salt. Have you not seen certain labourers when sowing a field with wheat for the second year in succession, burn the unused wheat straw which had been taken from the field? In the ashes will be found the salt that the straw took out of the soil ; if this is put back the soil is improved. Being burnt on the ground it serves as manure because it returns to the soil those substances that had been taken away." But for every speculation that has been confirmed will be found many that have not, and the beginnings of agricultural chemistry must be sought later, when men had learnt the necessity for carrying on experiments.

The Search for the " Principle " of Vegetation, 1630-1750.

The earlier investigators sought for a " principle " of vegetation to account for the phenomena of soil fertility and plant growth. The great Lord Bacon (8) believed that water formed the " principal nourishment " of plants, the purpose of the soil being to keep them upright and protect them from excessive cold or heat, but he also considered that each plant drew a " particular juyce " from the soil for its sustenance, thereby impoverishing the soil for that particular plant and similar ones, but not necessarily for other plants. Van Helmont regarded water as the sole nutrient for plants, and his son thus records his famous Brussels experiment (131): " I took an earthen vessel in which I put 200 pounds of soil dried in an oven, then I moistened with rain water and pressed hard into it a shoot of willow weighing 5 pounds. After exactly five years the tree that had grown up weighed 169 pounds and about three ounces. But the vessel had never received anything but rain water or distilled water to moisten the soil when this was necessary, and it remained full of soil, which was still tightly packed, and, lest any dust from outside should get into the soil, it was covered with a sheet of iron coated with tin but perforated with many holes. I did not take the weight of the leaves that fell in the autumn. In the end I dried the soil

once more and got the same 200 pounds that I started with, less about two ounces. Therefore the 164 pounds of wood, bark, and root, arose from the water alone."

The experiment is simple and convincing, and satisfied Boyle (50), who repeated it with "squash, a kind of Indian pompion" and obtained similar results. Boyle further distilled the plants and concluded, quite justifiably from his premises, that the products obtained, "salt, spirit, earth, and even oil (though that be thought of all bodies the most opposite to water), may be produced out of water". Nevertheless, the conclusion is incorrect, because two factors had escaped Van Helmont's notice—the parts played by the air and by the missing two ounces of soil. But the history of this experiment is thoroughly typical of experiments in agricultural chemistry generally: in no other subject is it so easy to overlook a vital factor and draw from good experiments a conclusion that appears to be absolutely sound, but is in reality entirely wrong.

Some years later—about 1650—Glauber (107) set up the hypothesis that saltpetre is the "principle" of vegetation. Having obtained saltpetre from the earth cleared out from cattle sheds, he argued that it must have come from the urine or droppings of the animals, and must, therefore, be contained in the animal's food, *i.e.* in plants. He also found that additions of saltpetre to the soil produced enormous increases in crop. He connected these two observations and supposed that saltpetre is the essential principle of vegetation. The fertility of the soil and the value of manures (he mentions dung, feathers, hair, horn, bones, cloth cuttings) are entirely due to saltpetre.

This view was supported by Mayow's experiments (195). He estimated the amounts of nitre in the soil at different times of the year, and showed that it occurs in greatest quantity in spring when plants are just beginning to grow, but is not to be found "in soil on which plants grow abundantly, the reason being that all the nitre of the soil is sucked out by the plants". Kübel (quoted in 293), on the other hand, regarded a *magma*

unguinum obtainable from humus as the "principle" sought for.

The most accurate work in this period was published by John Woodward, in a remarkable paper in 1699 (321). Setting out from the experiments of Van Helmont and of Boyle, but apparently knowing nothing of the work of Glauber and of Mayow, he grew spearmint in water obtained from various sources with the following results among others :—

| Source of Water. | Weight of Plants. | | Gained in 77 days. | Expense of Water (i.e. Transpiration). | Proportion of Increase of Plant to Expense of Water. |
|--------------------------|-------------------|-----------------|--------------------|--|--|
| | When put in. | When taken out. | | | |
| | Grains. | Grains. | Grains. | Grains. | |
| Rain water . . . | 28½ | 45½ | 17½ | 3004 | 1 to 171½ |
| River Thames . . | 28 | 54 | 26 | 2493 | 1 to 95½ |
| Hyde Park conduit | 110 | 249 | 139 | 13140 | 1 to 94½ |
| 1½ ozs. "garden mould" + | 92 | 376 | 284 | 14950 | 1 to 52½ |

Now all these plants had abundance of water, therefore all should have made equal growth had nothing more been needed. The amount of growth, however, increased with the impurity of the water. "Vegetables," he concludes, "are not formed of water, but of a certain peculiar terrestrial matter. It has been shown that there is a considerable quantity of this matter contained in rain, spring, and river water, that the greatest part of the fluid mass that ascends up into plants, does not settle there but passes through their pores and exhales up into the atmosphere: that a great part of the terrestrial matter, mixed with the water, passes up into the plant along with it, and that the plant is more or less augmented in proportion as the water contains a greater or less quantity of that matter; from all of which we may reasonably infer, that earth, and not water, is the matter that constitutes vegetables."

He discusses the use of manures and the fertility of the soil from this point of view, attributing the well-known falling off in crop yield when plants are grown for successive years on

unmanured land to the circumstance that "the vegetable matter that it at first abounded in being extracted from it by those successive crops, is most of it borne off. . . . The land may be brought to produce another series of the same vegetables, but not until it is supplied with a new fund of matter, of like sort with that it at first contained; which supply is made several ways, either by the ground's being fallow some time, until the rain has poured down a fresh stock upon it; or by the tiller's care in manuring it." The best manures, he continues, are parts either of vegetables or of animals, which ultimately are derived from vegetables.

In his celebrated textbook of chemistry Boerhaave (41) taught that plants absorb the juices of the earth and then work them up into food. The raw material, the "prime radical juice of vegetables, is a compound from all the three kingdoms, *viz.* fossil bodies and putrified parts of *animals* and *vegetables*". This "we look upon as the *chyle of the plant*; being chiefly found in the first order of vessels, *viz.*, in the roots and the body of the plant, which answers to the stomach and intestines of an animal".

For many years no such outstanding work as that of Glauber and Woodward was published, if we except Hales' *Vegetable Statics* (119), the interest of which is physiological rather than agricultural.¹ Advances were, however, being made in agricultural practice. One of the most important was the introduction of the drill and the horse hoe by Jethro Tull (286), an Oxford man of a strongly practical turn of mind, who insisted on the vital importance of getting the soil into a fine crumbly state for plant growth. Tull was more than an inventor; he discussed in most picturesque language the sources of fertility in the soil. In his view it was not the juices of the earth, but the very minute particles of soil loosened by the action of moisture, that constituted the "proper pabulum" of plants. The pressure caused by the swelling of the growing roots forced these particles into the "lacteal mouths of the roots," where they entered the circulatory system. All plants lived on these particles, *i.e.* on the

¹ He shows, however, that air is "wrought into the composition" of plants.

same kind of food ; it was incorrect to assert, as some had done, that different kinds of plants fed as differently as horses and dogs, each taking its appropriate food and no other. Plants will take in anything that comes their way, good or bad. A rotation of crops is not a necessity, but only a convenience. Conversely, any soil will nourish any plant if the temperature and water supply are properly regulated. Hoeing increased the surface of the soil or the "pasture of the plant," and also enabled the soil better to absorb the nutritious vapours condensed from the air. Dung acted in the same way, but was more costly and less efficient.

So much were Tull's writings esteemed, Cobbett tells us, that they were "plundered by English writers not a few and by Scotch in whole bandittis".

The position at the end of this period cannot better be summed up than in Tull's own words : "It is agreed that all the following materials contribute in some manner to the increase of plants, but it is disputed which of them is that very increase or food : (1) nitre, (2) water, (3) air, (4) fire, (5) earth".

The Search for Plant Nutrients.

1. *The Phlogistic Period, 1750-1800.*

Great interest was taken in agriculture in this country during the latter half of the eighteenth century. "The farming tribe," writes Arthur Young during this period, "is now made up of all ranks, from a duke to an apprentice." Many experiments were conducted, facts were accumulated, books written, and societies formed for promoting agriculture. The Edinburgh Society, established in 1755 for the improvement of arts and manufactures, induced Francis Home (137) "to try how far chymistry will go in settling the principles of agriculture". The whole art of agriculture, he says, centres in one point : the nourishing of plants. Investigation of fertile soils showed that they contain oil, which is therefore a food of plants. But when a soil has been exhausted by cropping, it recovers its

fertility on exposure to air,¹ which therefore supplies another food. Home made pot experiments to ascertain the effect of various substances on plant growth. "The more they (*i.e.* farmers) know of the effects of different bodies on plants, the greater chance they have to discover the nourishment of plants, at least this is the only road." Saltpetre, Epsom salt, vitriolated tartar (*i.e.* potassium sulphate) all lead to increased plant growth, yet they are three distinct salts. Olive oil was also useful. It is thus clear that plant food is not one thing only, but several; he enumerates six: air, water, earth, salts of different kinds, oil, and fire in a fixed state. As further proof he shows that "all vegetables and vegetable juices afford those very principles, and no other, by all the chymical experiments which have yet been made on them with or without fire".

The book is a great advance on anything that had gone before it, not only because it recognises that plant nutrition depends on several factors, but because it indicates so clearly the two methods to be followed in studying the problem—pot cultures and plant analysis. Subsequent investigators, Wallerius (293), the Earl of Dundonald (90), and Kirwan (149) added new details but no new principles. The problem indeed was carried as far as was possible until further advances were made in plant physiology and in chemistry. The writers just mentioned are, however, too important to be passed over completely. Wallerius, in 1761, professor of chemistry at Upsala, after analysing plants to discover the materials on which they live, and arguing that *Nutritio non fieri potest a rebus heterogeneis, sed homogeneis*, concludes that humus, being *homogeneis*, is the source of their food—the *nutritiva*—while the other soil constituents are *instrumentalia*, making the proper food mixture, dissolving and attenuating it, till it can enter the plant root. Thus chalk and probably salts help in dissolving the "fatness" of the humus. Clay helps to retain the "fatness" and prevent it being washed away by rain: sand keeps the soil open and pervious to air. The Earl of Dundonald, in

¹ Recorded by most early writers, *e.g.* Evelyn (*Terra*, 1674) (96).

1795, adds alkaline phosphates to the list of nutritive salts, but he attaches chief importance to humus as plant food. The "oxygenation" process going on in the soil makes the organic matter insoluble and therefore useless for the plant; lime, "alkalis and other saline substances" dissolve it and change it to plant food; hence these substances should be used alternately with dung as manure. Manures were thus divided, as by Wallerius, into two classes: those that afford plant food, and those that have some indirect effect.

Throughout this period it was believed that plants could generate alkalis. "Alkalies," wrote Kirwan in 1796, "seem to be the product of the vegetable process, for either none, or scarce any, is found in the soils, or in rain water." In like manner Lampadius thought he had proved that plants could generate silica. The theory that plants agreed in all essentials with animals was still accepted by many men of science; some interesting developments were made by Erasmus Darwin in 1803 (77).

Between 1770 and 1800 work was done on the effects of vegetation on air that was destined to revolutionise the ideas of the function of plants in the economy of Nature, but its agricultural significance was not recognised until later. In 1771 Priestley (230), knowing that the atmosphere becomes vitiated by animal respiration, combustion, putrefaction, etc., and realising that some natural purification must go on, or life would not longer be possible, was led to try the effect of sprigs of living mint on vitiated air. He found that the mint made the air purer, and concludes "that plants, instead of affecting the air in the same manner with animal respiration, reverse the effects of breathing, and tend to keep the atmosphere pure and wholesome, when it is become noxious in consequence of animals either living, or breathing, or dying, and putrefying in it". But he had not yet discovered oxygen, and so could not give precision to his discovery: and when, later on, he did discover oxygen and learn how to estimate it, he unfortunately failed to confirm his earlier results because he overlooked a vital factor, the necessity of light. He was therefore unable to

answer Scheele, who had insisted that plants, like animals, vitiate the air. It was Ingen-Housz (142) who reconciled both views and showed that purification goes on in light only, whilst vitiation takes place in the darkness. Jean Senebier at Geneva had also arrived at the same result. He also studied the converse problem—the effect of air on the plant, and in 1782 argued (259) that the increased weight of the tree in Van Helmont's experiment (p. 2) came from the fixed air. “Si donc l'air fixe, dissous dans l'eau de l'atmosphère, se combine dans la parenchyme avec la lumière et tous les autres élémens de la plante; si le phlogistique de cet air fixe est sûrement précipité dans les organes de la plante, si ce précipité reste, comme on le voit, puisque cet air fixe sort des plantes sous la forme d'air déphlogistiqué, il est clair que l'air fixe, combiné dans la plante avec la lumière, y laisse une matière qui n'y seroit pas, et mes expériences sur l'étiollement suffisent pour le démontrer.” Later on Senebier translated his work into the modern terms of Lavoisier's system.

2. *The Modern Period, 1800-1860.*

(a) *The Foundation of Plant Physiology.*—We have seen that Home in 1756 pushed his inquiries as far as the methods in vogue would permit, and in consequence no marked advance was made for forty years. A new method was wanted before further progress could be made, or before the new idea introduced by Senebier could be developed. Fortunately, this was soon forthcoming. To Théodore de Saussure, in 1804 (244), son of the well-known de Saussure of Geneva, is due the quantitative experimental method which more than anything else has made modern agricultural chemistry possible: which formed the basis of subsequent work by Boussingault, Liebig, Lawes and Gilbert, and indeed still remains our safest method of investigation. Senebier tells us that the elder de Saussure was well acquainted with his work, and it is therefore not surprising that the son attacked two problems that Senebier had also studied—the effect of air on plants and the nature and origin

of salts in plants. De Saussure grew plants in air or in known mixtures of air and carbon dioxide, and measured the gas changes by eudiometric analysis and the changes in the plant by "carbonisation". He was thus able to demonstrate the central fact of plant respiration—the absorption of oxygen and the evolution of carbon dioxide, and further to show the decomposition of carbon dioxide and evolution of oxygen in light. Carbon dioxide in small quantities was a vital necessity for plants, and they perished if it was artificially removed from the air. It furnished them not only with carbon, but also with some oxygen. Water is also decomposed and fixed by plants. On comparing the amount of dry matter gained from these sources with the amount of material that can enter through the roots even under the most favourable conditions, he concludes that the soil furnished only a very small part of the plant food. Small as it is, however, this part is indispensable: it supplies nitrogen—*une partie essentielle des végétaux*—which, as he had shown, was not assimilated direct from the air; and also ash constituents, *qui peuvent contribuer à former, comme dans les animaux, leur parties solides ou osseuses*. Further, he shows that the root is not a mere filter allowing any and every liquid to enter the plant; it has a special action and takes in water more readily than dissolved matter, thus effecting a concentration of the solution surrounding it; different salts, also, are absorbed to a different extent. Passing next to the composition of the plant ash, he shows that it is not constant, but varies with the nature of the soil and the age of the plant; it consists mainly, however, of alkalis and phosphates. All the constituents of the ash occur in humus. If a plant is grown from seed in water there is no gain in ash: the amount found at the end of the plant's growth is the same as was present in the seed excepting for a relatively small amount falling on the plant as dust. Thus he disposes finally of the idea that the plant *generated* potash.

After the somewhat lengthy and often wearisome works of the earlier writers it is very refreshing to turn to de Saussure's concise and logical arguments and the ample verification he

gives at every stage. But for years his teachings were not accepted, nor were his methods followed.

The two great books on agricultural chemistry then current still belonged to the old period. Thaer and Davy, while much in advance of Wallerius, the textbook writer of 1761, nevertheless did not realise the fundamental change introduced by de Saussure; it has always been the fate of agricultural science to lag behind pure science. Thaer published his *Grundsätze der rationellen Landwirtschaft* in 1809-1812: it had a great success on the Continent as a good, practical handbook, and was translated into English as late as 1844 by Cuthbert Johnson. Davy's book (79) grew out of the lectures which he gave annually at the Royal Institution on agricultural chemistry between 1802 and 1812; it was published in 1813, and forms the last textbook of the older period. Whilst no great advance was made by Davy himself (indeed his views are distinctly behind those of de Saussure) he carefully sifted the facts and hypotheses of previous writers, and gives us an account, which, however defective in places, represents the best accepted knowledge of the time, set out in the new chemical language. He does not accept de Saussure's conclusion that plants obtain their carbon chiefly from the carbonic acid of the air: some plants, he says, appear to be supplied with carbon chiefly from this source but in general he supposes the carbon to be taken in through the roots. Oils are good manures because of the carbon and hydrogen they contain; soot is valuable, because its carbon is "in a state in which it is capable of being rendered soluble by the action of oxygen and water". Lime is useful because it dissolves hard vegetable matter. Once the organic matter has dissolved there is no advantage in letting it decompose further: putrid urine is less useful as manure than fresh urine, whilst it is quite wrong to cause farmyard manure to ferment before it is applied to the land. All these ideas have long been given up, and indeed there never was any sound experimental evidence to support them. It is even arguable that they would not have persisted so long as they

did had it not been for Davy's high reputation. His insistence on the importance of the physical properties of soils—their relationship to heat and to water—was more fortunate and marks the beginning of soil physics, afterwards developed considerably by Schübler (254). On the Continent, to an even greater extent than in England, it was held that plants drew their carbon from the soil and lived on humus, a view supported by the very high authority of Berzelius.¹

(b) *The Foundation of Agricultural Science*.—Hitherto experiments had been conducted either in the laboratory or in small pots: about 1834, however, Boussingault, who was already known as an adventurous traveller in South America, began a series of field experiments on his farm at Bechelbronn in Alsace. These were the first of their kind: to Boussingault, therefore, belongs the honour of having introduced the method by which the new agricultural science was to be developed. He reintroduced the quantitative methods of de Saussure, weighed and analysed the manures used and the crops obtained, and at the end of the rotation drew up a balance sheet, showing how far the manure had satisfied the needs of the crop and how far other sources of supply—air, rain, and soil—had been drawn upon. The results of one experiment are given in Table I. on the opposite page. At the end of the period the soil had returned to its original state of productivity, hence the dry matter, carbon, hydrogen, and oxygen not accounted for by the manure must have been supplied by the air and rain, and not by the soil. On the other hand, the manure afforded more mineral matter than the crop took off, the balance remaining in the soil. Other things being equal, he argued that the best rotation is one which yields the greatest amount of organic matter over and above what is present in the manure. No fewer than five rotations were studied, but it will suffice to set out only the nitrogen statistics (Table II. on the opposite page), which show a marked gain of nitrogen

¹ J. J. Berzelius, *Lehrbuch d. chemie*, übersetzt. v. F. Wöhler, 3 Aufl., 1839, Bd. 8.

TABLE I.—STATISTICS OF A ROTATION. BOUSSINGAULT (46).

| | Weight in kilograms per hectare of | | | | | |
|--|------------------------------------|----------|-----------|----------|-----------|-----------------|
| | Dry Matter. | Carbon. | Hydrogen. | Oxygen. | Nitrogen. | Mineral Matter. |
| 1. Beets . . . | 3172 | 1357.7 | 184.0 | 1376.7 | 53.9 | 199.8 |
| 2. Wheat . . . | 3006 | 1431.6 | 164.4 | 1214.9 | 31.3 | 163.8 |
| 3. Clover hay . . . | 4029 | 1909.7 | 201.5 | 1523.0 | 84.6 | 310.2 |
| 4. Wheat . . . | 4208 | 2004.2 | 230.0 | 1700.7 | 43.8 | 229.3 |
| Turnips (catch crop) . . . | 716 | 307.2 | 39.3 | 302.9 | 12.2 | 54.4 |
| 5. Oats . . . | 2347 | 1182.3 | 137.3 | 890.9 | 28.4 | 108.0 |
| Total during rotation | 17478 | 8192.7 | 956.5 | 7009.0 | 254.2 | 1065.5 |
| Added in manure . . | 10161 | 3037.6 | 426.8 | 2621.5 | 203.2 | 3271.9 |
| Difference not accounted for, taken from air, rain, or soil. | + 7317 | + 4555.1 | + 529.7 | + 4387.5 | + 51.0 | + 2206.4 |

1000 kilograms per hectare = 16 cwt. per acre.

TABLE II.—NITROGEN STATISTICS OF VARIOUS ROTATIONS. BOUSSINGAULT (46).

| Rotation. | Kilograms per hectare. | | | |
|---|------------------------|-------------------|--|---------------------------|
| | Nitrogen in Manure. | Nitrogen in Crop. | Excess in Crop over that supplied in Manure. | |
| | | | Per Rotation. | Per Annum. |
| (1) Potatoes, (2) wheat, (3) clover, (4) wheat, turnips, ¹ (5) oats . . | 203.2 | 250.7 | 47.5 | 9.5 |
| (1) Beets, (2) wheat, (3) clover, (4) wheat, turnips, ¹ (5) oats . . | 203.2 | 254.2 | 51.0 | 10.2 |
| (1) Potatoes, (2) wheat, (3) clover, (4) wheat, turnips, ¹ (5) peas, (6) rye Jerusalem artichokes, two years | 243.8 188.2 | 353.6 274.2 | 109.8 86.0 | 18.3 43.0 ² |
| (1) Dunged fallow, (2) wheat, (3) wheat | 82.8 | 87.4 | 4.6 | 1.5 |
| Lucerne, five years | 224.0 | 1078.0 | 854 | 170.8 |

¹ Catch crop, i.e. taken in autumn after the wheat.² This crop does not belong to the leguminosæ, but it is possible that the nitrogen came from the soil, and that impoverishment was going on.

when the newer rotations are adopted, but not where wheat only is grown.

Now the rotation has not impoverished the soil, hence he concludes that "l'azote peut entrer directement dans l'organisme des plantes, si leur parties vertes sont aptes à le fixer". Boussingault's work covers the whole range of agriculture and deals with the composition of crops at different stages of their growth, with soils, and with problems in animal nutrition. Unfortunately the classic farm of Bechelbronn did not remain a centre of agricultural research and the experiments came to an end. Some of the work was summarised by Dumas in a very striking essay (88, see also 47) that has been curiously overlooked by agricultural chemists.

During this period (1830 to 1840) Carl Sprengel was studying the ash constituents of plants, which he considered were probably essential to nutrition (270). Schübler was working at soil physics (254), and a good deal of other work was quietly being done. No particularly important discoveries were being made, no controversies were going on, and no great amount of interest was taken in the subject.

But all this was changed in 1840 when Liebig's famous report to the British Association upon the state of organic chemistry, afterwards published as *Chemistry in its Application to Agriculture and Physiology* (174a), came like a thunderbolt upon the world of science. With polished invective and a fine sarcasm he holds up to scorn the plant physiologists of his day for their continued adhesion, in spite of accumulated evidence, to the view that plants derive their carbon from the soil and not from the carbonic acid of the air. "All explanations of chemists must remain without fruit, and useless, because, even to the great leaders in physiology, carbonic acid, ammonia, acids, and bases, are sounds without meaning, words without sense, terms of an unknown language, which awake no thoughts and no associations." The experiments quoted by the physiologists in support of their view are all "valueless for the decision of any question". "These experiments are considered by them as convincing proofs, whilst they are fitted only to

awake pity." Liebig's ridicule did what neither de Saussure's nor Boussingault's logic had done: it finally killed the humus theory. Only the boldest would have ventured after this to assert that plants derive their carbon from any source other than carbon dioxide, although it must be admitted that we have no proof that plants really do obtain all their carbon in this way. Thirty years later, in fact, Grandeau (112) adduced evidence that humus may, after all, contribute something to the carbon supply, and his view still finds acceptance in France;¹ for this also, however, convincing proof is lacking. But for the time carbon dioxide was considered to be the sole source of the carbon of plants. Hydrogen and oxygen came from water, and nitrogen from ammonia. Certain mineral substances were essential: alkalis were needed for neutralisation of the acids made by plants in the course of their vital processes, phosphates were necessary for seed formation, and potassium silicates for the development of grasses and cereals. The evidence lay in the composition of the ash: plants might absorb anything soluble from the soil, but they excreted from their roots whatever was non-essential. The fact of a substance being present was therefore sufficient proof of its necessity.

Plants, Liebig argued, have an inexhaustible supply of carbonic acid in the air. But time is saved in the early stages of plant growth if carbonic acid is being generated in the soil, for it enters the plant root and affords extra nutriment over and above what the small leaves are taking in. Hence a supply of humus, which continuously yields carbonic acid, is advantageous. Further, the carbonic acid attacks and dissolves some of the alkali compounds of the soil and thus increases the mineral food supply. The true function of humus is to evolve carbonic acid.

The alkali compounds of the soil are not all equally soluble. A weathering process has to go on, which is facilitated by liming and cultivation, whereby the comparatively insoluble

¹ See e.g. L. Cailletet (64), Jules Lefèvre (169), and J. Laurent, *Rev. gén. bot.*, 1904, 16, 14.

compounds are broken down to a more soluble state. The final solution is effected by acetic acid excreted by the plant root, and the dissolved material now enters the root.

The nitrogen is taken up as ammonia, which may come from the soil, from added manure, or from the air. In order that a soil may remain fertile it is necessary and sufficient to return in the form of manure the mineral constituents and the nitrogen that have been taken away. When sufficient crop analyses have been made it will be possible to draw up tables showing the farmer precisely what he must add in any particular case.

An artificial manure known as Liebig's patent manure was made up on these lines and placed on the market.

Liebig's book was meant to attract attention to the subject, and it did; it rapidly went through several editions, and as time went on Liebig developed his thesis, and gave it a quantitative form: "The crops on a field diminish or increase in exact proportion to the diminution or increase of the mineral substances conveyed to it in manure". He further adds what afterwards became known as the Law of the Minimum,¹ "by the deficiency or absence of *one* necessary constituent, all the others being present, the soil is rendered barren for all those crops to the life of which *that one* constituent is indispensable". These and other amplifications in the third edition, 1843, gave rise to much controversy. So much did Liebig insist, and quite rightly, on the necessity for alkalis and phosphates, and so impressed was he by the gain of nitrogen in meadow land supplied with alkalis and phosphates alone, and by the continued fertility of some of the fields of Virginia and Hungary and the meadows of Holland, that he began more and more to regard the atmosphere as the source of nitrogen for plants. Some of the passages of the first and second editions urging the necessity of ammoniacal manures were deleted from the third and later editions. "If the soil be suitable, if it con-

¹ The underlying principle was not discovered by Liebig, having already been enunciated by political economists of the Malthus School. He was, however, the first to apply it to plant nutrition.

tains a sufficient quantity of alkalis, phosphates, and sulphates, nothing will be wanting. The plants will derive their ammonia from the atmosphere as they do carbonic acid," he writes in the *Farmer's Magazine*.¹ Ash analysis led him to consider the turnip as one of the plants "which contain the least amount of phosphates and therefore require the smallest quantity for their development". These and other practical deductions were seized upon and shown to be erroneous by Lawes (161-162) who had for some years been conducting vegetation experiments. Lawes does not discuss the theory as such, but tests the deductions Liebig himself draws and finds them wrong. Further trouble was in store for Liebig; his patent manure when tried in practice *had failed*. This was unfortunate, and the impression in England at any rate was, in Philip Pusey's words: "The mineral theory, too hastily adopted by Liebig, namely, that crops rise and fall in direct proportion to the quantity of mineral substances present in the soil, or to the addition or abstraction of these substances which are added in the manure, has received its death-blow from the experiments of Mr Lawes".

And yet the failure of the patent manure was not entirely the fault of the theory, but only affords further proof of the numerous pitfalls of the subject. The manure was sound in that it contained potassium compounds and phosphates (it ought, of course, to have contained nitrogen compounds), but it was unfortunately rendered insoluble by fusion with lime and calcium phosphate so that it should not too readily wash out in the drainage water. Not till Way had shown in 1850 that *soil precipitates soluble salts of ammonium, potassium and phosphates* was the futility of the fusion process discovered, and Liebig saw the error he had made (174*b*).

Meanwhile the great field experiments at Rothamsted had been started by Lawes and Gilbert in 1843. These experiments were conducted on the same general lines as those begun

¹ *Farmer's Magazine*, 1847, vol. xvi., p. 511. A good summary of Liebig's position is given in his *Letters on Chemistry*, 34th letter, 3rd edition, p. 519, 1851.

earlier by Boussingault, but they have the advantage that they are still going on, having been continued year after year on the same ground without alteration, except in occasional details, since 1852. The mass of data now accumulated is considerable and it is being treated by modern statistical methods. Certain conclusions are so obvious, however, that they can be drawn on mere inspection of the data. By 1855 the following points were definitely settled (166*c*):—

(1) Crops require phosphates and salts of the alkalis, but the composition of the ash does not afford reliable information as to the amounts of each constituent needed, *e.g.* turnips require large amounts of phosphates, although only little is present in their ash. Some of the results are:—

| Composition of ash, per cent. (1860 crop)— | | | | Yield of turnips, tons per acre (1843)— | |
|---|---|---|------|---|------|
| K ₂ O | . | . | 44.8 | Unmanured | 4.5 |
| P ₂ O ₅ | . | . | 7.9 | Superphosphate | 12.8 |
| | | | | " + potassic salts | 11.9 |

(2) Non-leguminous crops require a supply of some nitrogenous compounds, nitrates and ammonium salts being almost equally good. Without an adequate supply no increases of growth are obtained, even when ash constituents are added. The amount of ammonia obtainable from the atmosphere is insufficient for the needs of crops. Leguminous crops behaved abnormally.

(3) Soil fertility may be maintained for some years at least by means of artificial manures.

(4) The beneficial effect of fallowing lies in the increase brought about in the available nitrogen compounds in the soil.

Although many of Liebig's statements were shown to be wrong, the main outline of his theory as first enunciated stands. It is no detraction that de Saussure had earlier published a somewhat similar, but less definite view of nutrition: Liebig had brought matters to a head and made men look at their cherished, but unexamined, convictions. The effect of the stimulus he gave can hardly be over-

estimated, and before he had finished, the essential facts of plant nutrition were settled and the lines were laid down along which scientific manuring was to be developed. The water cultures of Knop and other plant physiologists showed conclusively that potassium, magnesium, calcium, iron, phosphorus, along with sulphur, carbon, nitrogen, hydrogen, and oxygen are all necessary for plant life. The list differs from Liebig's only in the addition of iron and the withdrawal of silica; but even silica, although not strictly essential, is advantageous to cereals.

In two directions, however, the controversies went on for many years. Farmers were slow to believe that "chemical manures" could ever do more than stimulate the crop, and declared they must ultimately exhaust the ground. The Rothamsted plots falsified this prediction; manured year after year with the same substances and sown always with the same crops, they even now, after sixty years of chemical manuring, continue to produce good crops, although secondary effects have sometimes set in. In France the great missionary was Georges Ville, whose lectures were given at the experimental farm at Vincennes during 1867 and 1874-5 (288). He went even further than Lawes and Gilbert, and maintained that artificial manures were not only more remunerative than dung, but were the only way of keeping up fertility. In recommending mixtures of salts for manure he was not guided by ash analysis but by field trials. For each crop one of the four constituents, nitrogen compounds, phosphates, lime, and potassium compounds (he did not consider it necessary to add any others to his manures) was found by trial to be more wanted than the others and was therefore called the "dominant" constituent. Thus for wheat he obtained the following results, and therefore concluded that on his soil wheat required a good supply of nitrogen, less phosphate, and still less potassium:—

| | Crop per acre. Bushels. |
|-------------------------------|----------------------------|
| Normal manure | 43 |
| Manure without lime | 41 |
| " " potash | 31 |
| " " phosphate | 26½ |
| " " nitrogen | 14 |
| Soil without manure | 12 |

Other experiments of the same kind showed that nitrogen was the dominant for all cereals and beetroot, potassium for potatoes and vines, phosphates for the sugar cane. An excess of the dominant constituent was always added to the crop manure. The composition of the soil had to be taken into account, but soil analysis was no good for the purpose. Instead he drew up a simple scheme of plot trials to enable farmers to determine for themselves just what nutrient was lacking in their soil. His method was thus essentially empirical, but it still remains the best we have; his view that chemical manures are always better and cheaper than dung is, however, too narrow and has not survived.

The second controversy dealt with the source of nitrogen in plants. Priestley had stated that a plant of *Epilobium hirsutum* placed in a small vessel absorbed during the course of the month seven-eighths of the air present. De Saussure, however, denied that plants assimilated gaseous nitrogen. Boussingault's pot-experiments showed that peas and clover could get nitrogen from the air while wheat could not (45), and his rotation experiments emphasised this distinction. He himself did not make as much of this discovery as he might have done, but Dumas (88) fully realised its importance.

Liebig, as we have seen, maintained that ammonia, but not gaseous nitrogen, was taken up by plants, a view confirmed by Lawes, Gilbert, and Pugh (164) in the most rigid demonstration that had yet been attempted. Plants of several natural orders, including the leguminosæ, were grown in surroundings free from ammonia or any other nitrogen compound. The soil was burnt to remove all trace of nitrogen compounds while the plants were kept throughout the ex-

periment under glass shades, but supplied with washed and purified air and with pure water. In spite of the ample supply of mineral food the plants languished and died: the conclusion seemed irresistible that plants could not utilise gaseous nitrogen. For all non-leguminous crops this conclusion agreed with the results of field trials. But there remained the very troublesome fact that leguminous crops required no nitrogenous manure and yet they contained large quantities of nitrogen, and also enriched the soil considerably in this element. Where had the nitrogen come from? The amount of combined nitrogen brought down by the rain was found to be far too small to account for the result. For years experiments were carried on, but the problem remained unsolved. Looking back over the papers¹ one can see how very close some of the older investigators were to the discovery of the cause of the mystery: in particular Lachmann (158) in 1858 and Bretschneider (54) in 1861. Lachmann showed that the nodules invariably present on the roots contained "vibrionenartige" organisms, while Bretschneider showed that the nitrogen fixation which occurred in normal soil did not take place in ignited soil. But these papers were both published in obscure journals and attracted little attention, and once again an investigation in agricultural chemistry had been brought to a standstill for want of new methods of attack.

The Beginnings of Soil Bacteriology.

It had been a maxim with the older agricultural chemists that "corruption is the mother of vegetation". Animal and vegetable matter had long been known to decompose with formation of nitrates: indeed nitre beds made up from such decaying matter were the recognised source of nitrates for the manufacture of gunpowder during the European Wars of the seventeenth and eighteenth centuries.² No satisfactory

¹ A good summary of the voluminous literature is contained in Löhnis *Handbuch der Landw. Bakteriologie*, pp. 646 et seq.

² "Instructions sur l'établissement des nitrières, publié par les Régisseurs généraux des Poudres et Salpêtre. Paris, 1777.

explanation of the process had been offered, although the discussion of rival hypotheses continued up till 1860, but the conditions under which it worked were known and on the whole fairly accurately described.

No connection was at first observed between nitrate formation and soil productiveness. Liebig rather diverted attention from the possibility of tracing what now seems an obvious relationship by regarding ammonia as the essential nitrogenous plant nutrient, though he admitted the possible suitability of nitrates (174*c*). Way came much nearer to the truth. In 1856 (298*b*) he showed that nitrates were formed in soils to which nitrogenous fertilisers were added. Unfortunately he failed to realise the significance of this discovery. He was still obsessed with the idea that ammonia was essential to the plant, and he believed that ammonia, unlike other nitrogen compounds, could not change to nitrate in the soil, but was absorbed by the soil by the change he had already described (p. 17). But he only narrowly missed making an important advance in the subject, for after pointing out that nitrates are comparable with ammonium salts as fertilisers he writes: "Indeed the French chemists are going further, several of them now advocating the view that it is in the form of nitric acid that plants make use of compounds of nitrogen. With this view I do not myself at present coincide: and it is sufficient here to admit that nitric acid in the form of nitrates has at least a very high value as a manure."

It was not till ten years later, and as a result of work by plant physiologists, that the French view prevailed over Liebig's and agricultural investigators recognised the importance of nitrates to the plant and of nitrification to soil fertility. It then became necessary to discover the cause of nitrification.

During the sixties and seventies great advances were being made in bacteriology, and it was definitely established that bacteria bring about putrefaction, decomposition and other changes; it was therefore conceivable that they were the active agents in the soil and that the process of decom-

position there taking place was not the purely chemical "eremacausis" Liebig had postulated. Pasteur himself had expressed the opinion that nitrification was a bacterial process. The new knowledge was first brought to bear on agricultural problems by Schloesing and Müntz (245) in 1877 during a study of the purification of sewage water by land filters. A continuous stream of sewage was allowed to trickle down a column of sand and limestone so slowly that it took eight days to pass. For the first twenty days the ammonia in the sewage was not affected, then it began to be converted into nitrate; finally all the ammonia was converted during its passage through the column, and nitrates alone were found in the issuing liquid. Why, asked the authors, was there a delay of twenty days before nitrification began? If the process were simply chemical, oxidation should begin at once. They therefore examined the possibility of bacterial action and found that the process was entirely stopped by a little chloroform vapour, but could be started again after the chloroform was removed by adding a little turbid extract of dry soil. Nitrification was thus shown to be due to micro-organisms—"organised ferments," to use their own expression.

Warington (295-6) had been investigating the nitrates in the Rothamsted soils, and at once applied the new discovery to soil processes. He showed that nitrification in the soil is stopped by chloroform and carbon disulphide; further, that solutions of ammonium salts could be nitrified by adding a trace of soil. By a careful series of experiments described in his four papers to the Chemical Society he found that there were two stages in the process and two distinct organisms: the ammonia was first converted into nitrite and then to nitrate. But he failed altogether to obtain the organisms, in spite of some years of study, by the gelatin plate methods then in vogue. The reason was discovered later: the organisms will not grow in presence of nitrogenous organic matter. Not till 1890 did Winogradsky (311) succeed in isolating them, and thus complete the evidence.

Warington established definitely the fact that nitrogen

compounds rapidly change to nitrates in the soil, so that whatever compound is supplied as manure plants get practically nothing but nitrate as food. This closed the long discussion as to the nitrogenous food of non-leguminous plants; in natural conditions they take up nitrates only (or at any rate chiefly), because the activities of the nitrifying organisms leave them no option. The view that plants assimilate gaseous nitrogen has from time to time been revived,¹ but has not been taken seriously.

TABLE III.—RELATION BETWEEN NITROGEN SUPPLY AND PLANT GROWTH.
HELLRIEGEL AND WILFARTH (130).

| Nitrogen in the calcium nitrate supplied per pot, grams | none | '056 | '112 | '168 | '224 | '336 |
|---|--------------------------|------------------------------|------------------------------|---------|----------------------|---------|
| Weight of oats obtained (grain and straw) | { '3605 '4191 | { 5'9024 5'8510 5'2867 | { 10'9814 10'9413 | 15'6974 | { 21'2732 21'4409 | 30'1750 |
| Weight of peas obtained (grain and straw) | { '551 3'496 5'233 | { '9776 1'3037 4'1283 | { 4'9146 9'7671 8'4969 | 5'6185 | { 9'7252 6'6458 | 11'3520 |

The apparently hopeless problem of the nitrogen nutrition of leguminous plants was soon to be solved. In a striking series of sand cultures Hellriegel and Wilfarth (130) showed that the growth of non-leguminous plants, barley, oats, etc., was directly proportional to the amount of nitrate supplied, the duplicate pots agreeing satisfactorily; while in the case of leguminous plants no sort of relationship existed and duplicate pots failed to agree. After the seedling stage was passed the leguminous plants grown without nitrate made no further progress for a time, then some of them started to grow and did well, while others failed. This stagnant period was not seen where nitrate was supplied. Two of their experiments are given in Table III.

Analysis showed that the nitrogen contained in the oat crop and sand at the end of the experiment was always a little less than that originally supplied, but was distinctly greater in the case of peas; the gain in three cases amounted to '910,

¹ e.g. see (224b).

1·242 and ·789 grm. per pot respectively. They drew two conclusions: (1) the peas took their nitrogen from the air; (2) the process of nitrogen assimilation was conditioned by some factor that did not come into their experiment except by chance. In trying to frame an explanation they connected two facts that were already known. Berthelot (26) had made experiments to show that certain micro-organisms in the soil can assimilate gaseous nitrogen. It was known to botanists that the nodules on the roots of leguminosæ contained bacteria.¹ Hellriegel and Wilfarth, therefore, supposed that the bacteria in the nodules assimilated gaseous nitrogen, and then handed on some of the resulting nitrogenous compounds to the plant. This hypothesis was shown to be well founded by the following facts:—

1. In absence of nitrates peas made only small growth and developed no nodules in sterilised sand; when calcium nitrate was added they behaved like oats and barley, giving regular increases in crop for each increment of nitrates (the discordant results of Table II. were obtained on unsterilised sand).

2. They grew well and developed nodules in sterilised sand watered with an extract of arable soil.

3. They sometimes did well and sometimes failed when grown without soil extract and without nitrate in *unsterilised* sand, which might or might not contain the necessary organisms. An extract that worked well for peas might be without effect on lupins or serradella. In other words, the organism is specific.

Hellriegel and Wilfarth read their paper and exhibited some of their plants at the Naturforscher-Versammlung at Berlin in 1886. Gilbert was present at the meeting, and on returning to Rothamsted repeated and confirmed the experiments (165). At a later date Schloesing fils and Laurent

¹ This had been demonstrated by Lachmann in 1858 (158) (p. 21) and by Woronin in 1866 (322). Eriksson in 1874 (Doctor's dissertation, abs. in *Botan. Ztg.*, 1874, 32, 381-384) carried on the investigation, while Brunchorst in 1885 *Ber. d. Deutsch. Bot. Ges.* iii., 241-257, gave the name "bacteroids".

(247) showed that the weight of nitrogen absorbed from the air was approximately equal to the gain by the plant and the soil, and thus finally clinched the evidence.

| | Control. | Peas. | Mustard. | Cress. | Spurge. |
|--|----------|-------|----------|--------|---------|
| Nitrogen lost from the air, mgm. | 1'0 | 134'6 | - 2'6 | - 3'8 | - 2'4 |
| Nitrogen gained by crop and soil, mgm. | 4'0 | 142'4 | - 2'5 | 2'0 | 3'2 |

The organism was isolated by Beijerinck (p. 204) and called *Bacterium radicola*.

Thus another great controversy came to an end, and the discrepancy between the field trials and the laboratory experiments of Lawes, Gilbert, and Pugh was cleared up. The laboratory experiments gave the correct conclusion that leguminous plants, like non-leguminous plants, have themselves no power of assimilating gaseous nitrogen; this power belongs to the bacteria associated with them. But so carefully was all organic matter removed from the soil, the apparatus, and the air in endeavouring to exclude all trace of ammonia, that there was no chance of infection with the necessary bacteria. Hence no assimilation could go on. In the field trials the bacteria were active, and here there was a gain of nitrogen.

The general conclusion that bacteria are the real makers of plant food in the soil, and are, therefore, essential to the growth of all plants, was developed by Wollny (317*b*) and Berthelot (28). It was supposed to be proved by Laurent's experiments (160, see also 87). He grew buckwheat on humus obtained from well-rotted dung, and found that plants grew well on the untreated humus, but only badly on the humus sterilised by heat. When, however, soil bacteria were added to the sterilised humus (by adding an aqueous extract of unsterilised soil) good growth took place. The experiment looks convincing, but is really unsound. When a rich soil is heated some substance is formed toxic to plants. The failure of the plants on the sterilised humus was, therefore, not due to absence of bacteria, but to the presence of a toxin.

No one has yet succeeded in carrying out this fundamental experiment of growing plants in two soils differing only in that one contains bacteria while the other does not.

Similarly Caron¹ thought he had direct evidence of the beneficial effect of bacteria in plant growth, but in reality the evidence is unsatisfactory.

The close connection between bacterial activity and the nutrition of plants is, however, fully justified by many experiments, and forms a considerable part of our modern conception of the soil as a producer of crops, as will appear in the following chapters.

The Rise of Modern Knowledge of the Soil: the Search for Fresh Factors and for Mathematical Expressions.

Further investigation of soil problems has shown that they are more complex than was at first supposed. The older workers had thought of soil fertility as a simple chemical problem; the early bacteriologists thought of it as bacteriological. It was demonstrated by F. H. King at Wisconsin (147*a*) that physical considerations must also be taken into account. Van Bemellen showed that soil has colloidal properties and present-day workers have reproduced in the soil many of the phenomena investigated in laboratories devoted to the study of colloids. Whitney and Cameron at Washington greatly widened the subject by revealing the importance of the soil solution and introducing the methods and principles of physical chemistry. Russell and Hutchinson at Rothamsted showed that bacterial action alone would not account for the biological phenomena in the soil, but that other organisms are also concerned, and subsequent work in the Rothamsted laboratories has revealed the presence of a complex soil population, the various members of which react on one another and on the growing plant. Fresh advances are continually being made in the vigorous experiment stations in the United States, the British Empire, Japan, and Europe.

In the main the work is analytical and involves a search

¹ *Landw. Versuchs. Stat.*, 1895, **45**, 401-418.

for new factors: synthesis is hardly attempted as yet. As the factors are discovered attempts are made to give them mathematical expression. Thus Liebig's Law of the Minimum and F. F. Blackman's Limiting Factors are expressed mathematically by Mitscherlich (p. 32): V. H. Blackman¹ expresses plant growth by the "compound interest law": Miyake (pp. 185 and 188) brings ammonification and nitrification within the equation for autocatalytic actions; and the modern agricultural chemist is acquiring a taste for mathematical formulæ and constants unknown to the older generation of workers.

This attempt to find mathematical expressions has been resisted on two grounds: some suppose that phenomena associated with life cannot in any case be expressed mathematically and that nothing but a hollow appearance of agreement can be obtained; others consider that the mathematical formula, if it is to hold at all, must be expressed in such general terms as to become meaningless, *e.g.* many of the actions going on in Nature can be expressed by exponential equations if the terms are chosen with sufficient ingenuity. The soil investigator, however, will be wise to secure all the assistance he can, as the subject is complex, and it cuts across the conventional divisions of science.

In modern Experimental Stations the tendency is towards team work. As an instance chosen because it is best known to the writer: at the Rothamsted Experimental Station, instead of a number of isolated individuals, there is a body of workers investigating the subject, each from his own special point of view, but each fully cognisant of the work of the others, and periodically submitting his results to discussion by them. Separate workers investigate respectively the bacteria, protozoa, fungi, algæ, helminths, and insects of the soil; in addition physical and organic chemists are studying the soil conditions, while others are concerned in the study of the growing plant. A body of workers by harmonious co-operation is able to make advances that would be impossible for any single individual, however brilliant.

¹ *Annals of Botany*, 1919, 33, 353.

The nature of the subject necessitates a further departure from the usual procedure. In purely laboratory investigations it is customary to adopt the Baconian method in which factors are studied one at a time, all others being kept constant except the particular one under investigation. In dealing with soils in natural conditions, however, it is impossible to proceed in this way: climatic factors will not be kept constant, and however careful the effort to ensure equality of conditions there is always the probability, and sometimes the certainty, that the variable factor under investigation is interacting with climatic factors and exerting indirect effects which modify or even obscure the direct effects it is desired to study.

Of recent years statisticians have devised methods for dealing with cases where several factors are varying simultaneously. The data obtained by the various workers at Rothamsted are therefore examined by a statistician who endeavours to disentangle the effects of various factors and to state a number of probable relationships which can then be investigated in the laboratory by the ordinary single factor method.

The modern methods as applied at Rothamsted include three distinct processes:—

1. Observations or experiments in the field by a group of specialists working independently, but with full cognisance of each other's results.
2. Examination of the data by modern statistical methods so as to ascertain the probable effects of the known factors and to indicate where known factors are insufficient to account for the results, and where, therefore, new factors must be sought.
3. Laboratory studies by the specialist staff of the relationships indicated by the statistical examination, these being reduced to single factor problems.

CHAPTER II.

SOIL CONDITIONS AFFECTING PLANT GROWTH.

IN order to put limits to our discussion, it is necessary at the outset to state what soil factors influence plant growth and how, in general, the influence is manifested. We shall, therefore, in the present chapter bring together certain of the results obtained by plant physiologists which are indispensable for the proper study of the subject.

It has been shown that the five following soil factors profoundly affect the growth of plants :—

1. Water supply.
2. Air supply.
3. Temperature.
4. Supply of plant nutrients.
5. Various injurious factors.

The plant may be affected in two general ways—in the amount of growth (*i.e.* the total amount of dry matter formed), or in the habit or other characteristic of growth. The former is susceptible of quantitative investigation, the latter is not, or only with difficulty ; it has, therefore, proved less attractive to investigators.

The Effect on the Amount of Growth.

1. *The Study of Single Factors.*

Of the five factors concerned plant nutrients are, on the whole, the easiest to investigate quantitatively. The general relationship between the supply of a given plant nutrient and the amount of dry matter formed was demonstrated by Hellriegel at Dhome in the eighties of the last century. Barley

was grown in pots of sand, all necessary factors were amply provided, excepting only potassium salts, the amount of which varied in the different pots. The weights of dry matter formed are shown in Table IV.

TABLE IV.—EFFECT OF POTASSIUM SALTS ON GROWTH OF BARLEY
HELLRIEGEL (1904).

| Mgms. of K ₂ O per pot. | 0 | 23.5 | 47 | 70.5 | 94 | 188 | 282 |
|------------------------------------|-------|-------|-------|--------|--------|--------|--------|
| Dry matter formed when | | | | | | | |
| KCl was given | 2.271 | 5.414 | 9.024 | 9.963 | 15.322 | 21.246 | 24.417 |
| K ₂ SO ₄ " | 2.519 | 5.140 | 5.283 | 13.363 | 14.768 | 21.593 | 23.774 |
| KNO ₃ " | — | 4.552 | 6.621 | 9.919 | 14.576 | 21.499 | 24.206 |
| KH ₂ PO ₄ " | — | 4.687 | 6.346 | 9.931 | 12.377 | 17.171 | — |
| K ₂ HPO ₄ " | — | — | 6.684 | — | 11.730 | 20.255 | — |
| Average | 2.410 | 4.948 | 6.791 | 10.001 | 13.755 | 20.357 | 24.132 |

These results are plotted in Fig. 1.

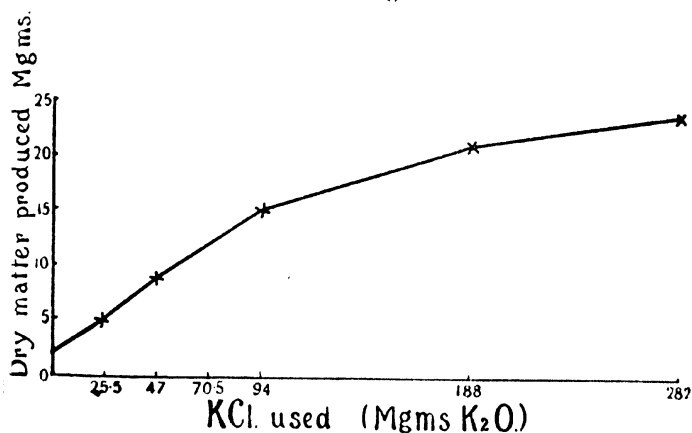


FIG. 1.—Relation between potash supply and growth of barley (Hellriegel).

Similar curves are obtained when the varying nutrient is nitrogen or phosphorus.

The smoothness of the curve suggests that it can be expressed by a mathematical equation, and E. A. Mitscherlich has attempted to do this, proceeding in the following manner: If all the conditions were ideal, a certain maximum yield would be obtained, but in so far as any essential factor is deficient

there is a corresponding shortage in the yield. The yield rises if some of the lacking factor is added, and goes up all the further the lower it had previously fallen. Mitscherlich put this as follows: the increase of crop produced by unit increment of the lacking factor is proportional to the decrement

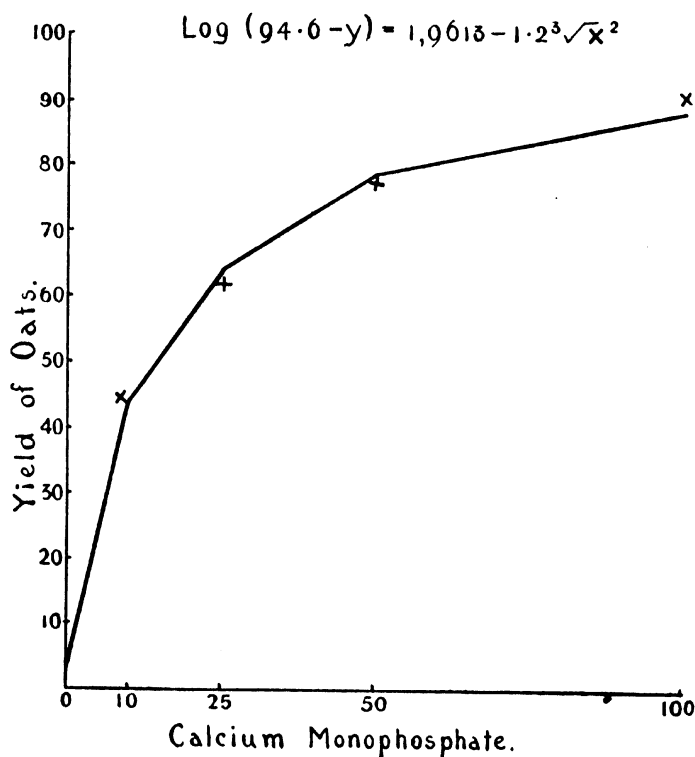


FIG. 2.—Mitscherlich's curve showing relation between yield of oats and amount of phosphate supplied.

from the maximum. The advantages of this form is that it can be expressed mathematically:—

$$\frac{dy}{dx} = (A - y)k \text{ or } \log_e(A - y) = c - kx,$$

where y is the yield obtained when x = the amount of the

factor present and A is the maximum yield obtainable if the factor were present in excess, this being calculated from the equation.

Mitscherlich's own experiments were made with oats grown in sand cultures supplied with excess of all nutrients excepting phosphate. This constituted the variable x : the yields actually attained when monocalcium phosphate was used and those calculated from the equation shown in Table V. (Fig. 2).

Experiments were also made with di- and tri-calcic phosphates and constants were calculated corresponding to k .

The ratio of these constants

$$\frac{k_2(\text{di-calcic phosphate})}{k_1(\text{mono-calcic phosphate})}$$

is a measure of the relative nutrient efficiency of the two salts; k is therefore called the efficiency value (Wirkungswert). There are some very attractive possibilities about this method of treatment, since it gives a constant independent of the yield and having a definite mathematical meaning.¹

TABLE V.—YIELD OF OATS WITH DIFFERENT DRESSINGS OF PHOSPHATES.
MITSCHERLICH (201*b*).

| P ₂ O ₅ in Manure. | Dry Matter Produced. | Crop Calculated from Formula. | Difference. | Difference × Probable Error. |
|--|----------------------|-------------------------------|-------------|------------------------------|
| Grams. | Grams. | Grams. | | |
| 0·00 | 9·8 ± 0·50 | 9·80 | — 0·39 | — 0·8 |
| 0·05 | 19·3 ± 0·52 | 18·91 | — 0·56 | — 0·3 |
| 0·10 | 27·2 ± 2·00 | 26·64 | — 2·37 | — 2·8 |
| 0·20 | 41·0 ± 0·85 | 38·63 | + 3·22 | + 2·9 |
| 0·30 | 43·9 ± 1·12 | 47·12 | + 2·49 | + 0·7 |
| 0·50 | 54·9 ± 3·66 | 57·39 | + 6·64 | + 3·0 |
| 2·00 | 61·0 ± 2·24 | 67·64 | — | — |

The method has given rise to considerable controversy in

¹ For an interesting application see *Zur Frage der Wurzelauausscheidungen der Pflanze* (Landw. Versuchs-Stat., 1913, lxxxi., 467-474), in which Mitscherlich argues that the root excretions of clover cannot differ from those of oats.

Germany. Pfeiffer¹ insists that the curves must be profoundly modified by other limiting factors, while Fröhlich takes exception to the method of calculation.² Mitscherlich apparently recognises the force of these criticisms, for he now admits that Liebig's Law of the Minimum is not a correct expression of the facts: the yield is determined not by the one factor which is lacking, but by all the factors. Baule (9) has developed an equation on these lines which, he claims, agrees satisfactorily with the experimental results.

Curves of similar type have been obtained for variations in water supply and in temperature, but owing to greater experimental difficulties the data are less reliable, and, therefore, not susceptible to mathematical treatment. The temperature results are of interest, in that they bring out an important differ-

¹ Th. Pfeiffer, E. Blanck, and M. Flügel, *Wasser und Licht als Vegetations-factoren und ihre Beziehungen zum Gesetze von Minimum* (Landw. Versuchs-Stat., 1912, lxxvi., 169-236. See also 224e).

² The method of calculation is as follows: Obtain two equations by substituting two of the numerical values of x and y obtained experimentally. Calling these numbers x_1 , x_2 , etc., the equations are

$$\log_e (A - y_1) = c - kx_1 \quad . \quad . \quad . \quad (1)$$

$$\log_e (A - y_2) = c - kx_2 \quad . \quad . \quad . \quad (2)$$

$$\text{Then by subtraction } \log (A - y_1) - \log (A - y_2) = k (x_2 - x_1) \quad . \quad . \quad (3)$$

Obtain another equation like (3) but select the numerical values so that

$$\begin{aligned} x_3 - x_2 &= x_2 - x_1 \\ \log_e (A - y_2) - \log_e (A - y_3) &= k (x_3 - x_2) \quad . \quad . \quad (4) \end{aligned}$$

By subtracting (4) from (3) $\log_e (A - y_1) + \log_e (A - y_3) = 2 \log_e (A - y_2)$,

$$\text{i.e. } \frac{(A - y_3)(A - y_1)}{(A - y_2)^2} = 1 \quad . \quad . \quad (5)$$

Since y_1 , y_2 , and y_3 are all known, the value of A is easily calculated.

The value of k is then found from equation (3)

$$k = \frac{\log_e(A - y_1) - \log_e(A - y_2)}{x_2 - x_1}$$

As all the quantities on the right-hand side are known the value of k is readily obtained. A difficulty is that different values for A are, in fact, obtained when other equations like (3) are worked out. If there were a very large number of points, a probable value for A could be obtained: with a small number, such as almost necessarily are obtained in practice, some selection apparently has to be made, which is objectionable. This was done by Mitscherlich in the case quoted in Table V.

ence between sustained growth and the individual processes of assimilation, etc. In the classical experiments of F. F. Blackman and of Miss Matthaei (now A. G. L. Howard) (193) the effect of temperature on assimilation, all other factors being eliminated, was precisely that obtaining in an ordinary chemical reaction ; so also for respiration. Miss Matthaei found that the amounts of carbon dioxide assimilated by a cherry laurel leaf per 30 sq. cms. (about 8 sq. ins.) per hour at various temperatures were :—

| | | | | | | | | | |
|--|-------|--------|-------|-------|-------|-------|-------|-------|------------------|
| Temperature, deg. C. | - 6° | + 8·8° | 11·4° | 15° | 23·7° | 30·5° | 37·5° | 40·5° | 43° ¹ |
| Weight of CO ₂ assimilated, grams | ·0002 | ·0038 | ·0048 | ·0070 | ·0102 | ·0157 | ·0238 | ·0149 | ·0102 |

By interpolation, the values at 0°, 10°, 20°, etc., can be found, and the rate of assimilation is thus seen approximately to double for every increase of 10°, the usual order of increase in chemical reactions :—²

| | | | | | |
|--|------|-----|-----|-----|-----|
| Temperature | 0° | 10° | 20° | 30° | 37° |
| Amount of CO ₂ assimilated per hour | 17·5 | 42 | 89 | 157 | 238 |
| Increased rate for 10° C. | — | 2·4 | 2·1 | 1·8 | 1·8 |

But on the other hand, the effect of temperature on the rate of growth of a plant as a whole is in no wise like its effect in accelerating chemical change. Bialoblocki's (37) results with barley were as follows :—

| | | | | | |
|--------------------------|-------|------|------|------|------|
| Temperature | (0) | 10° | 20° | 30° | 40° |
| Dry matter formed, grams | (nil) | 7·64 | 8·22 | 3·85 | 0·93 |

The two curves are shown in Fig. 3 ; the difference between

¹ The rates were maintained only for a short time at the higher temperatures.

² A list of the papers dealing with the temperature co-efficient for cell growth is given in *Science*, 6th November, 1908. See also Zaleski, W., *Ber. Deut. Bot. Ges.*, 1909, 27, 56-62.

them is of fundamental importance to our subject and must be discussed in some detail.

Each of the separate processes—assimilation, respiration,

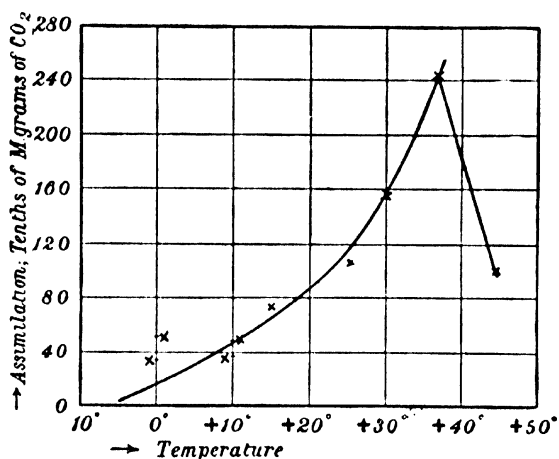


FIG. 3.—Relation between temperature and assimilation. (Miss Matthaei.)

etc., gives, so far as is known, curves like Fig. 3, continuous over the whole range of temperature nearly up to the death point. At higher temperatures it is necessary to work for a

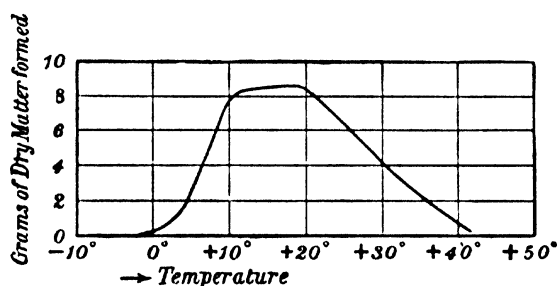


FIG. 3a.—Relation between temperature and plant growth. (Bialoblocki.)

short period only, so as to reduce the injurious effects then produced, but there is no break in the curve.

For the growth of the plant, however, it is necessary that all the processes should work harmoniously together, and that

the protoplasm should remain healthy and vigorous. Now the temperature range over which protoplasm lives and the somewhat delicate adjustment of the processes holds together is very restricted; beyond a certain point, which varies with different plants, further temperature increases do not cause more growth, but throw the adjustment out of gear. Thus the curve begins to bend over.

The student will observe a close similarity between this

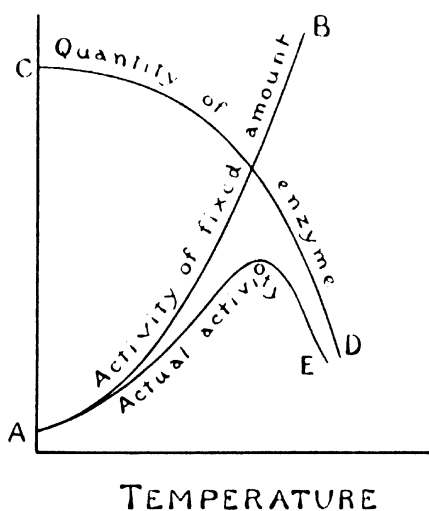


FIG. 4.—Influence of temperature on enzyme action, showing fall in quantity but increase in activity as temperature rises. (Duclaux.)

curve and that obtained by Duclaux¹ for the relation between enzyme action and temperature. In Fig. 4 AB shows the relation between enzyme action and temperature so long as the activity remains unimpaired; CD shows the relation between temperature and quantity of enzyme, the enzyme being destroyed as the temperature rises; AOE is the resultant curve showing the relation between temperature and the activity of a given initial quantity of enzyme.

¹ E. Duclaux, *Traité de Microbiologie*, Tome 2, Paris, 1899.

In this case the falling off in activity at higher temperatures (OE) is due to the destruction of the enzyme; in the case of the plant it is attributable to two factors, disadjustment of processes and injury to protoplasm.

(2) *Variation of Two or more Factors.*

The simple case presented by single factor variation is unusual in natural conditions; more generally two or more factors are present in quantities insufficient for perfect growth. This case has been discussed by F. F. Blackman who has introduced the very happy phrase "limiting factor" to express a conception previously used by H. T. Brown under the name "throttle valve". Generally speaking the effect of each separate factor is expressible by the single factor curve up to the point where a second factor begins to be insufficient, and then the curve alters considerably: instead of going on continuously the increase of growth falls off considerably or even is brought to an end. A factor that thus proves insufficient and stops or greatly retards what ought to be a continuous process is called a "limiting factor". Growth is once more resumed when the amount of the limiting factor is increased until again this factor proves insufficient, or some new factor comes into play.

These phenomena are illustrated by von Seelhorst's investigations on the effect of water supply on plant growth. In one of their investigations Tucker and von Seelhorst (256) put up three series of soil pots in which the water was kept at a definite amount; one was just moist, another was moister, and a third still moister. These were then each subdivided into three others, one receiving no nitrogen compounds, another one dose, and the third two doses. Oats were sown in all nine sets with results that are given in Table VI.

When only little water is present the added 0.5 grm. of nitrogen is without effect, the supply in the soil being sufficient for the crop needs: the water and not the nitrogen is the limiting factor. When more water is added the plant can

make more growth, and can therefore utilise more nitrogen : the added 0.5 gm. now raises the crop by 10 grms. Again, however, the water supply sets a limit, and the second 0.5 gm. of nitrogen is without effect. When a liberal supply of water is added the first 0.5 gm. of nitrogen gives 20 grms. of crop, double the previous increment ; but even this does not represent the whole possibility, for the second 0.5 gm. of nitrogen gives a still further increase of 15.5 grms.

TABLE VI.—INFLUENCE OF WATER SUPPLY ON THE EFFECTIVENESS OF MANURES. VON SEELHORST AND TUCKER (250).

Dry Weight of Oat Crop.

| Manuring. | Nitrogen Series. | | | Increased Crop for | |
|----------------------------|------------------|-------|--------------------|------------------------------|-------------------------------|
| | KP. | KPN. | KP ₂ N. | First Increment of Nitrogen. | Second Increment of Nitrogen. |
| I. Moist soil ¹ | 67.5 | 68.5 | 68.5 | 1.0 | 0 |
| II. Moister soil | 83.0 | 93.4 | 94.0 | 9.8 | .6 |
| III. Wettest soil | 99.5 | 119.5 | 135.0 | 20.0 | 15.5 |

K = 1 gram of K₂O as K₂CO₃ per pot ; P = 1 gram of P₂O₅ as Ca(H₂PO₄)₂ per pot ; N = .75 gram of N as NaNO₃ per pot.

| Manuring. | Phosphate Series. | | | | First Increment of P. | Second Increment of P. | Increase for Complete Manure, KNP. |
|----------------------------|-------------------|------|-------|--------------------|-----------------------|------------------------|------------------------------------|
| | None. | KN. | KNP. | KN ₂ P. | | | |
| I. Moist soil ¹ | 41.5 | 38.5 | 68.5 | 79.2 | 30.0 | 16.7 | 27 |
| II. Moister soil | 47.2 | 40.0 | 93.4 | 108.0 | 53.4 | 14.6 | 46.2 |
| III. Wettest soil | 68.5 | 63.5 | 119.5 | 127.5 | 56.0 | 8 | 51 |

The results of the phosphate series are somewhat different in detail, but not in principle. The first dose of P₂O₅ in the dry soil gives an increased crop, and so does the second, the first not having been large enough ; in the wetter soil, however, the increase is much larger. There is a still further increase in the wettest soil, but less than before, some other limiting

¹ The moist soil contained 14.35 per cent. of water (41.6 per cent. of saturation), the moister soil 15.41 per cent. at the beginning, increasing to 18.43 (51.7 per cent. of saturation) as the experiment proceeded, and the wettest soil, 16.44 per cent. at the beginning, increasing to 22.59 (63.7 per cent. of saturation).

factor now coming in. These relations are shown in the curves of Fig. 5.

A further illustration is afforded by experiments made by the writer on the growth of tomatoes in pots of sand in which supplies both of water and of nitrate were varied. The results are shown in the curves of Fig. 6. The series of curves is expressible by a surface, which is the proper way of representing the effect of two varying factors on plant growth. No account was taken of temperature variations; to do this would

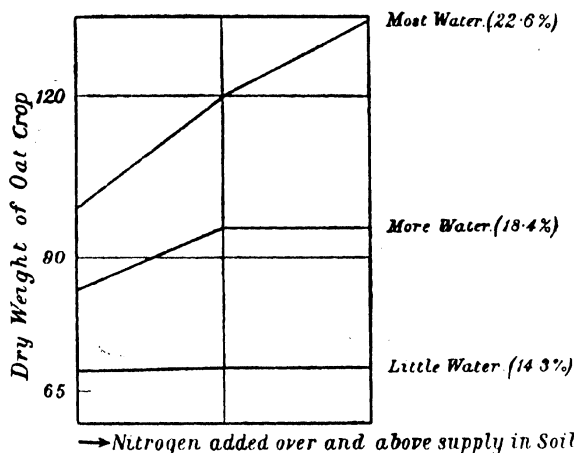


FIG. 5.—Influence of water supply on the effectiveness of manures. (Von Seelhorst and Tucker.)

necessitate the construction of a series of surfaces each valid for a particular temperature, or to adopt some mathematical device equivalent to projection in a fourth dimension.

In all these experiments it has been assumed that the observed effect is caused by the direct action of the added substance on the plant, and the assumption is justifiable because the plant is grown in sand which is very inert. When, however, a step nearer to natural conditions is taken, and the experiment is carried out in soil it is no longer safe to assume that the soil remains unaltered while the conditions are varied.

Experiments on the growth of tomatoes in soil made

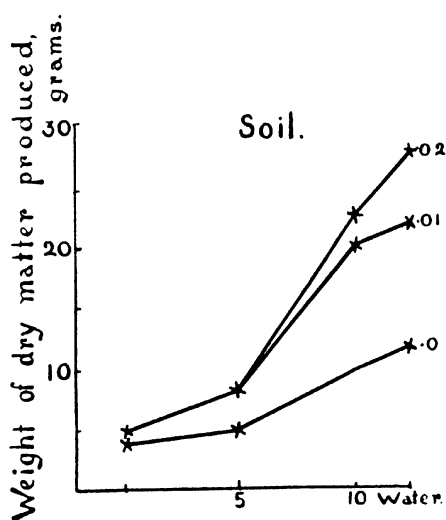
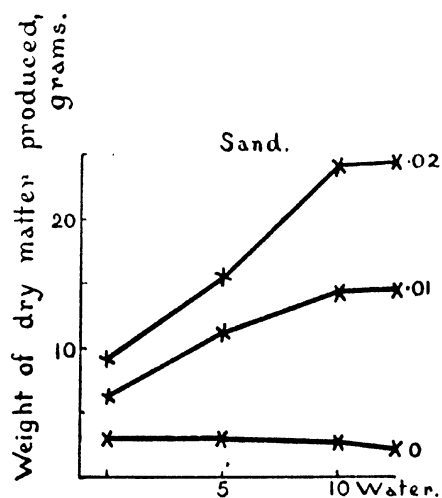


FIG. 6.—Effect of varying water and nitrate supply on the growth of tomatoes in pots of sand and of soil. (E. J. Russell.)

simultaneously with those in sand gave a very different result owing to interactions in the soil which will be discussed later. It is evident, however, that the soil must be studied dynamically and not statically. While the curve is still of the general type it differs from those obtained in sand in that there are now a number of factors concerned and the final result cannot be expressed by a surface or by a series of surfaces, but would involve something equivalent to projection into an n th dimension, an operation not within the scope of ordinary simple mathematics.

The general result of the quantitative work is that the

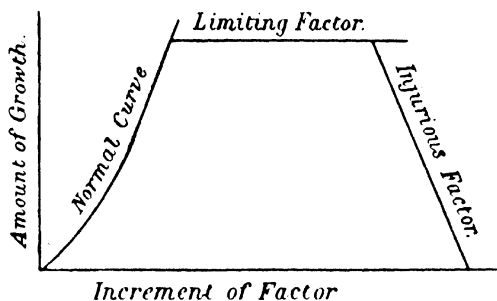


FIG. 7.—General relation between any particular factor and plant growth. An increment in the factor causes increases in growth up to the point when some second factor sets a limit; further increases then have no effect. Finally, excess of the factor may cause positive injury.

numerous soil factors involved in plant growth can be disentangled and separately studied. The operation of each factor is expressed by a curve which would probably be like Figs. 1 or 3, flattening out and finally bending over when larger amounts of the factor exert a harmful effect. In actual natural conditions the case is complicated by the fact that two or more factors are almost always concerned, one of which acts as a limiting factor. The curves are of the general type of Fig. 7.

Any possibility of simple mathematical treatment of the amount of growth in soil is ruled out by the circumstance that the various factors act not only on the plant, but also on the

soil, which in turn, reacts on the plant growth. If mathematical treatment is to be attempted it must be on statistical lines.

The Effect on the Habit of Growth or Other Plant Characteristics.

Hitherto, we have dealt only with the actual weight of the plant. Observations in the plant culture house or in the field, however, show that two plants may have the same weight and yet differ considerably in appearance, in proportion of root or of seed to leaf and stem, in degree of maturation and in other respects. These differences are often of considerable technical importance, profoundly affecting the value of the crop, and they are of great interest as indicators of soil conditions. It cannot, of course, be assumed that a certain appearance or character in the plant is always and necessarily produced by the same soil conditions, but the appearances are often symptomatic and serve to narrow the problem. The detailed discussion of these differences is the province of the modern science of Ecology, but the general results are of great importance to the soil student.¹ They will be dealt with under the headings of the separate factors.

Effect of Water Supply.

Water.—The relationship between the amount of growth and the supply of water is shown by Hellriegel's experiments (130a, Table VII.) with barley grown under favourable conditions in sand cultures.

The yield rises as the water increases up to a certain point, and then falls off because the excess of water reduces the air supply for the roots.

The grain suffers sooner than the leaves and stems. When a series of plants is grown in this way, with varying water supply, certain important qualitative differences are revealed.

¹ For an example of a survey carried out on these lines, see T. H. Kearney; L. J. Briggs, H. L. Shantz, J. W. McLane, and R. L. Piemeisel, *Indicator Significance of Vegetation in Tooele Valley, Utah, Journ. Ag. Research*, 1914, 1, 365-417.

Those receiving only small amounts of water, have small glaucous leaves and tend early to form seed. As the water supply increases, the root system increases rapidly both in extent and in fineness; with further supplies, the leaves become successively larger and greener in colour, ripening becomes delayed, but the root system becomes restricted and alters in character, finally consisting of a few stout roots only. Von Seelhorst (257*b*) has made quantitative determinations of the proportions of root system to entire plant under conditions of varying water supply.

TABLE VII.—GROWTH OF BARLEY WITH VARYING SUPPLY OF WATER.
HELLRIEGEL (130*a*).

| | | | | | | | |
|---------------------------|-----|------|------|------|-------|-------|------|
| Amount of water . . . | 5 | 10 | 20 | 30 | 40 | 60 | 80 |
| Dry matter in grain, gms. | nil | 0.72 | 7.75 | 9.73 | 10.51 | 9.96 | 8.77 |
| Dry matter in straw, gms. | .12 | 1.80 | 5.50 | 8.20 | 9.64 | 11.00 | 9.47 |
| 1 grain weighed, mgms. | — | 23 | 35 | 36 | 34 | 32 | 32 |

100 represents the amount of water required to saturate the sand.

These morphological differences are accompanied by differences in chemical composition of the plant. Even the seed is affected, a phenomenon which does not usually occur when other factors such as supplies of plant nutrients are varied. Thus the composition of the wheat grain is hardly affected by manuring, but it is profoundly altered by variations in water supply¹ (Shutt, 265). Other instances have been recorded

¹ C. H. Bailey, *Minnesota Expt. Sta. Bull.*, 131, 1913, has drawn up the following table, showing the protein content of the wheat and flour of the hard spring wheat grown in sixteen counties in Minnesota (1st April to 1st September, 1911).

| Rainfall. | Protein per cent. Wheat. | Protein per cent. Flour. |
|--------------------|--------------------------------|--------------------------------|
| Between 12-13 ins. | 14.93 | 13.47 |
| " 14-15 " | 13.73 | 12.61 |
| " 16-17 " | 12.21 | 12.56 |
| " 18-19 " | 13.42 | 12.29 |
| " 20-21 " | 12.88 | 11.87 |
| " 22-24 " | 11.63 | 10.65 |

Stewart and Hirst, *Utah Expt. Sta. Bull.*, 125, p. 145, obtained the following results at Utah, showing the effects of irrigation.

by von Seelhorst (257*d*), and by Pfeiffer, Blanck, and Friske (224*e*).

In soil, other and indirect factors come into play ; too much water causes the exclusion of air ; certain reduction products are then formed by bacteria which have a direct toxic effect on the plant.

These relationships are constantly recurring in field observations. On moist soils—clays and loams—the plants usually have large wide leaves and grow to a considerable size, whilst on the drier sands the vegetation is narrow leaved and more stunted, but the root system is well developed.¹ A copious water supply leads to a more protracted growth and to a retardation of the ripening processes ; indeed, in very wet districts, wheat and barley are grown only with difficulty, if at all, because ripening may be so long delayed that frosts supervene and damage the crop. Oats are less affected, as they are usually cut before they are ripe.

Water supply and temperature are the two chief factors determining the distribution of crops. In the warm, dry, eastern counties of Great Britain crops are grown for seed ; great quantities of wheat and barley are grown in Norfolk, Suffolk, and the Isle of Thanet ; mangold seed and turnip seed is produced in East Kent. Wetter districts are more favourable for swedes and oats ; very wet districts for grass. The warm, moist, south-west of Cornwall is very favourable for early vegetables, cabbage, cauliflower, etc., whilst the cooler Lincolnshire and Cheshire are well suited to potatoes. It is possible by suitable operations to modify somewhat both the temperature and the water content of the soil, and so to make

Footnote continued from opposite page—

| Irrigation. | Protein per cent. |
|----------------|-------------------|
| 25 ins. | 16·23 |
| 15 " | 12·92 |
| No irrigation. | 13·62 |

For the small effect of soil conditions see *Washington Ag. Expt. Sta. Bull.*, 111, and A. D. Hall, *Journ. Bd. Agric.*, 1904, 2, 321. Sodium hydrate and magnesium oxide affect the composition (pp. 73, 75).

¹See p. 310 *et seq.*

the soil conditions rather more favourable for any particular crop.

Some interesting results are obtained in glass house practice. Tomato growers have learned to regulate water supply and temperature in such a way as to produce compact bushy plants, which they know by experience give more fruit than the softer, larger plants, obtainable under other conditions. Until the blossom is fertilised or has "set," therefore, vigorous growth is not encouraged, and, in many cases, while the atmosphere is artificially damped, water is actually withheld from the roots until, in the picturesque language of the grower, "the plants cry for it". After "setting," water is liberally supplied and top dressings of manure are given.

It is impossible at present to make a complete analysis of these phenomena. The osmotic pressure of the plant cell is known to alter with changes in moisture content of the soil, and it may, and probably does, react on other characteristics of the plant. Some of Iljin's results (141) are given in Table VIII.

TABLE VIII.—CHANGE IN OSMOTIC PRESSURE OF PLANT CELL WITH CHANGES IN MOISTURE CONTENT OF SOIL.

| Ratio of Soil Moisture to Absolute Water Capacity of Soil. | Osmotic Pressure in Normal Solution of NaCl. ¹ | |
|--|---|------------------|
| | <i>Helianthus annuus.</i> | <i>Zea Mays.</i> |
| 80 per cent. | 0·14-0·16 | 0·17 |
| 60 „ | 0·25-0·28 | 0·19 |
| 30 „ | 0·41-0·45 | 0·49 |

Effect of Soil Conditions on Consumption of Water by the Plant.

In the experimental work just described the water content of the soil is kept artificially constant, thus eliminating the effect of the rate of consumption by the plant. In natural conditions, however, the supply is not maintained constant and the rate of consumption therefore becomes an important factor. Many determinations have been made of the weight of the water transpired per gram of dry matter formed, the figure being called the *transpiration coefficient*. This mode of

¹ 0·1 normal NaCl has an osmotic pressure of approximately 4 atmospheres.

expression is convenient and it gives useful information to the practical grower in irrigated districts, but from the strictly scientific point of view it suffers from the disadvantage that it implies a causal relationship between transpiration and assimilation when in reality there is none.

The transpiration coefficient is not constant but varies with the plant and the conditions, increasing with the temperature and to some extent with the water supply, but decreasing as the food supply increases.

TABLE IX.—TRANSPIRATION COEFFICIENTS, *i.e.* AMOUNT OF WATER TRANSPIRED DURING THE PRODUCTION OF ONE PART OF DRY MATTER. BRIGGS AND SHANTZ (55c).

| Crop. | Extreme Values for Different Varieties. | Mean Value for Genus. |
|--|--|--------------------------|
| Proso | 268 to 341 | 293 |
| Millet | 261 to 444 | 310 |
| Sorghum | 285 to 467 | 322 |
| Maize | 315 to 413 | 368 |
| Wheat | 473 to 559 | 513 |
| Barley | 502 to 556 | 534 |
| Oats | 559 to 622 | 597 |
| Flax | — | 905 |
| Sugar beet | — | 397 |
| Potato | — | 636 |
| Cow pea | — | 571 |
| Clover | 789 to 805 | 797 |
| Lucerne | 651 to 963 | 831 |
| Grasses | — | 861 |
| Various native plants (<i>i.e.</i> weeds) | 277 to 1076 | — |

With the plant variations we are not concerned. It is demonstrated, however, that a difference exists between different varieties of the same crop and that there are considerable prospects for breeding or selecting varieties specially suited for dry conditions. This work is already in hand with good results in Australia, the Western States and elsewhere. Unfortunately no correlation has been traced between water requirements and plant structure, so that the breeder has no guide in his selection except actual and tedious trials.

The effect of soil conditions has been studied at the Besentchuk Agricultural Experiment Station, Samara, Russia, situated in a district which suffers from prolonged summer drought and excessive variations in crops. The transpiration

coefficient is found to vary from year to year with the external meteorological conditions, being greatest in dry years and lowest in wet years; it is also higher in wet soils than in dry ones. Toulaikoff considers that it is these conditions, rather than the biological character of the plant, that determines the magnitude of the coefficient (284).

Some of his results are :—

| | 1911. | 1912. | 1913. | 1914. |
|-------------------------|-------|-------|-------|-------|
| Wheat, var. Polltawka . | 628.4 | 444.5 | 338.6 | 387.6 |
| " " Bieloturka . | 756.3 | 475.9 | 316.5 | 397.1 |
| Oats " Giant . | 655.1 | 510.3 | 347.4 | 369.9 |
| Barley " Moravian . | 617.9 | 461.6 | 230.3 | 413.3 |

The year 1911 was excessively dry, 1913 was very rainy; 1912 was an average year and 1914 was rather dry.

The effect of variations in water and food supply on the water requirements of plants was studied by Hellriegel, and subsequently by von Seelhorst at Göttingen (256-258), who has worked extensively at the various water relationships of plants. His results with oats are given in Table X.

TABLE X.—EFFECT OF VARYING WATER SUPPLY¹ AND FOOD SUPPLY ON THE WATER REQUIREMENTS OF OATS. VON SEELHORST (257a).

| | Dry Matter Produced, Grams. | | | Total Water Transpired, Grams. | | | Water Transpired per Gram of Dry Matter. | | |
|---------------------|--------------------------------|------------------|---------------------------|-----------------------------------|------------------|---------------------------|---|------------------|---------------------------|
| | Soil Moist. | Soil Moister. | Soil still Moister. | Soil Moist. | Soil Moister. | Soil still Moister. | Soil Moist. | Soil Moister. | Soil still Moister. |
| No manure | 39.6 | 48.8 | 52.6 | 10.215 | 15.245 | 16.290 | 259.9 | 312.9 | 307.1 |
| Complete manure. | 49.9 | 86.7 | 95.1 | 11.170 | 20.490 | 23.030 | 225.1 | 236.8 | 231.6 |

¹ The variations in water supply were :—

| | 5 to 12 May. | 12 May to 1 June. | 1 June to 1 July. |
|----------------------|--------------|-------------------|-------------------|
| Soil moist . . | 54.4 | 54.4 | 44.8 |
| Soil moister . . | 59.2 | 64.0 | 59.2 |
| Soil still moister . | 64.0 | 73.9 | 73.6 |

Where 100 = saturation of the soil.

Similar results have been obtained by Wilfarth (Table XI.), (1909a) with sugar beets grown in pots of soil containing known it varying amounts of nitrate.

TABLE XI.—EFFECT OF VARYING FOOD SUPPLY ON THE WATER REQUIREMENTS OF SUGAR BEET. WILFARTH.

| | | | | | | |
|--|--------|--------|--------|--------|--------|--------|
| Nitrogen supplied, grams . . . | 42 | 126 | 210 | 294 | 336 | 378 |
| Weight of dry matter produced, grams . . . | 230 | 739 | 965 | 1324 | 1676 | 1888 |
| Water transpired, grams . . . | 13,100 | 34,570 | 39,420 | 55,190 | 62,600 | 72,280 |
| Water stated as inches of rain . . . | 3.6 | 9.4 | 10.7 | 15.8 | 17.0 | 19.6 |
| Water used per gram of dry matter formed . . . | 569 | 468 | 409 | 417 | 374 | 383 |

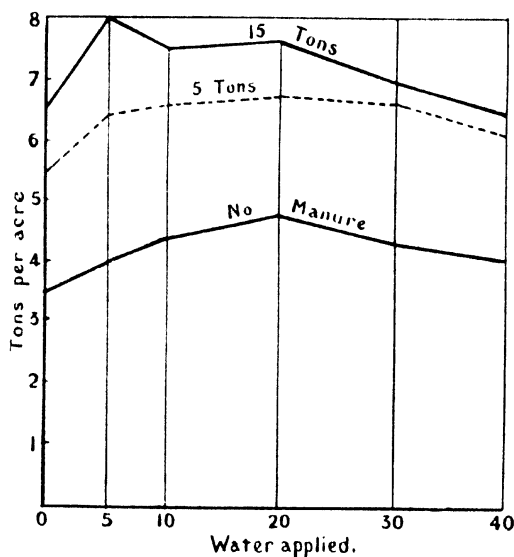


FIG. 8.—Effect of water supply on the effectiveness of farmyard manure. Yield of maize (stover and grain) in tons per acre for 0 to 40 inches irrigation water. (Harris and Butt, Utah, 123.)

Two deductions may be drawn: (1) water is economised by increasing the food supply; (2) the total amount of water required during the growing season may be greater than is supplied by the rain, in which case the balance must be otherwise provided, or the food cannot be utilised.

Over large areas of the world the rainfall is insufficient, and recourse is had to irrigation. In endeavouring to ascertain the best way of irrigating crops two considerations have to be kept in view: (1) excessive watering has secondary injurious effects on the soil, such as the deterioration of the physical condition, the accumulation of alkali salts, or the formation of toxic reduction products; (2) the requirements of the plant are not always the same, more water being needed during the period of active growth than during germination or ripening.

Some of the results obtained in Utah are set out in Table XII. and in Fig. 8:—

TABLE XII.—AVERAGE YIELD OF DRY MATTER AND NITROGEN FROM THE EXPERIMENTAL PLOTS ON GREENVILLE FARM, UTAH. GREAVES, STEWART, AND HIRST (113*b*).

(Expressed as lbs. per Acre.)

| Water Applied. | Lucerne. | | Potatoes. | |
|----------------|----------|-----------|-----------|-----------|
| | Hay. | Nitrogen. | Tubers. | Nitrogen. |
| ins. | | | | |
| 37'5 | 10,464 | 282'5 | 1,464 | 20'4 |
| 25'0 | 9,903 | 265'0 | 1,540 | 24'8 |
| 15'0 | 9,779 | 259'1 | 1,759 | 33'2 |
| None | 6,808 | 170'1 | 1,075 | 19'1 |

| Water Applied. | Oats. | | | Maize. | | |
|----------------|--------|--------|-----------|--------|---------|-----------|
| | Grain. | Straw. | Nitrogen. | Grain. | Stover. | Nitrogen. |
| ins. | | | | | | |
| 37'5 | 2,273 | 2,989 | 89'5 | 2,080 | 3,316 | 66'3 |
| 25'0 | 2,093 | 2,581 | 83'9 | 1,995 | 3,332 | 69'6 |
| 15'0 | 1,885 | 1,821 | 71'7 | 2,179 | 3,605 | 76'6 |
| None | 1,560 | 1,928 | 64'0 | 1,600 | 3,280 | 62'3 |

Field experiments like those conducted by the Punjab Irrigation Department¹ have shown that the cultivator every-

¹ These and similar experiments are discussed by A. and G. L. C. Howard in *Wheat in India: Its Production, Varieties, and Improvement* (Imperial Department of Agriculture, India, 1909). German experience is recorded in *Erfahrung bei der Ackerbewässerung* (*Jahrb. Deutsch. Landw. Gesell.*, 1913, 28, 76).

where tends to take too much water, with loss not only to others on the same irrigation system, but also to himself.

Air Supply.

It is well known among farmers and gardeners that soil aeration is essential to fertility but exact measurements are difficult to obtain. The phenomena are more complex than appears at first sight, involving two wholly distinct factors:—

1. The necessity of a supply of oxygen to the plant root.
2. The toxic effect of the carbon dioxide which invariably accumulates in a non-aerated soil or other medium.

Moreover, plants vary considerably in their sensitiveness to these factors.

The simplest case is seen in water cultures where aeration produces marked effects. In the experiments of Hall, Brenchley, and Underwood (121c) the amounts of dry matter produced were as follows:—

| | Barley, Grams per Plant. | Lupins, Grams per Plant. |
|--------------------------------|--------------------------------|--------------------------------|
| Non-aerated | 1.314 | 0.83 |
| Continuously aerated | 2.122 | 1.53 |

The more recent experiments of E. E. Free (100a) show that plants do not all stand in equal need of oxygen. Buckwheat was grown in water cultures through one set of which was blown air, and through others nitrogen, oxygen, and carbon dioxide respectively. No difference was observable between the plants supplied with nitrogen and those supplied with air or oxygen: they all grew normally to maturity. In this case, therefore, the root apparently can dispense with gaseous oxygen. When, however, carbon dioxide was given the plants sickened and wilted within a few hours, and died in a few days.

Stiles and Jørgensen (272) have confirmed this difference between barley and buckwheat.

Soil experiments are more difficult to carry out. B. E.

Livingstone and E. E. Free (178*c*) grew plants in soil so sealed that its atmosphere could be controlled. Different plants varied in their susceptibility to the exclusion of oxygen; *Coleus blumei* and *Heliotropium peruvianum* were the most sensitive, the intake of water in their roots ceasing within 12 to 24 hours owing to death of the roots and the entire plants ultimately died when oxygen was replaced by nitrogen. *Salix nigra*, on the other hand, successfully endured the exclusion of oxygen.

Application of these general results to field conditions have been made in India by A. and G. L. C. Howard (139), who have shown that increased soil aeration resulting from lessened irrigation or addition of potsherds to the soil leads to increased plant growth. Some of their results are given in Table XIII. :—

TABLE XIII.—THE EFFECT OF DILUTING THE PUSA SOIL WITH POTSHERDS OR SAND. A. AND G. L. C. HOWARD (139).

| Crop. | Yield per Acre of Control Plot. | Yield per Acre with 1 in. of Potsherds. | Increase per Acre. | Percentage Increase. |
|---------------|------------------------------------|---|-----------------------|-------------------------|
| | lb. | lb. | lb. | |
| Oats . . . | 1954 | 2312 | 358 | 18 |
| Wheat . . . | 1316 | 1580 | 264 | 20 |
| Tobacco . . . | 1680 | 1846 | 166 | 10 |

EFFECT OF REDUCING IRRIGATION AND THEREBY INCREASING AIR SUPPLY.
WHEAT.

| | Three Waterings. | Two Waterings. | One Watering. |
|-----------------|------------------|----------------|---------------|
| Yield of wheat: | | | |
| Grain lb. | 1222 | 1302 | 788 |
| Straw, etc. lb. | 1764 | 2004 | 1714 |

Hall, Brenchley, and Underwood (121*d*) found considerable differences in the amount of growth of lupins in sand and kaolin on the one hand, where ample aeration was possible, and fine sand, silt, or water culture on the other where there was much less aeration. Their results are :—

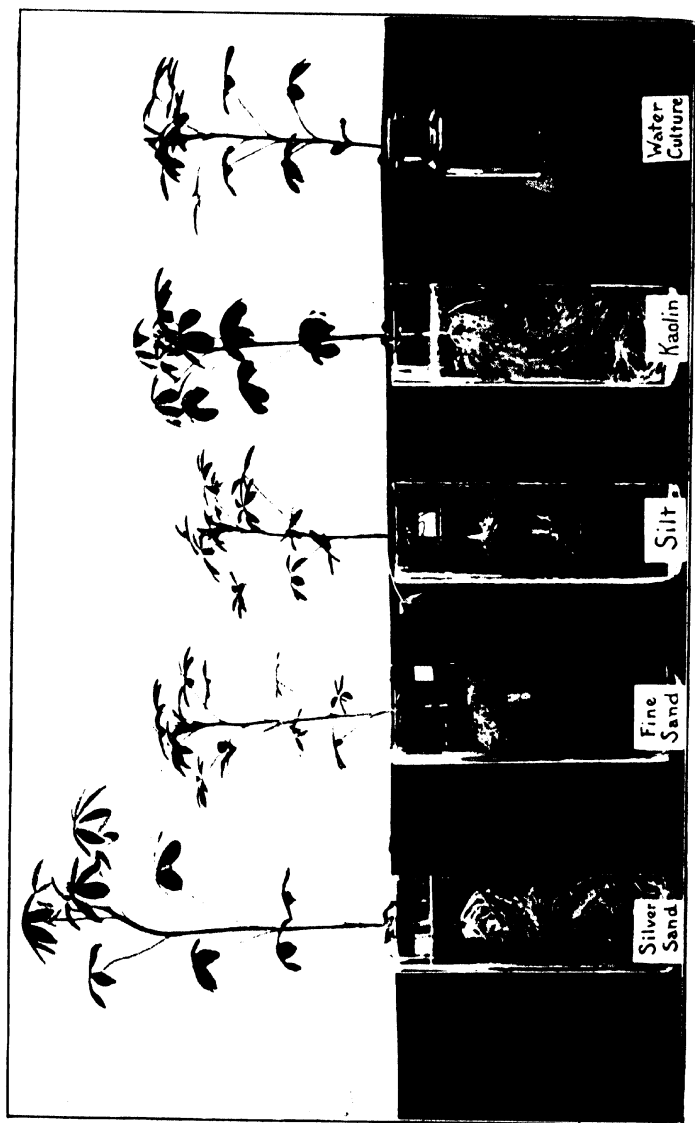


FIG. 1. — Effect of different media on the growth of the plant.

| | Weight of Dry Matter Formed, Grams. |
|--|--|
| Material allowing diffusion of air: Coarse sand . | 2'474 |
| Kaolin . . . | 1'833 |
| Material allowing less diffusion of air: Fine sand | 1'131 |
| Silt . . . | 1'393 |
| Water . . . | 1'942 |

The results are illustrated in Fig. 9.¹

Temperature.

It is difficult to separate soil temperature effects from temperature effects in general, and in practice the distinction is unnecessary since the temperature of the air is largely determined by that of the soil.

The effect of temperature shows itself in three ways:—

1. It profoundly affects the rate of growth of plants, and thus determines what plants can be grown and what cannot be grown in a given area.

If the temperature is too low a yellow or purplish colour may appear in the leaf, and the plant grows so slowly that it is liable in its early stages to succumb to insect pests, such as wireworms, and in its later stages to be cut down by autumn frosts before it has time to ripen. If, on the other hand, the temperature is too high, the plant becomes taller than usual, less robust and, when much water is also supplied, liable to fungoid pests that prove very troublesome in commercial glasshouses. Only over a comparatively restricted range of temperature is it possible to obtain the compact sturdy habit aimed at by the grower. This favourable range has not yet been correlated with other properties of the plant and has to be discovered empirically; it is, on the whole, lower for the seedling than for the growing plant, but it is highest for the period of maturation. It varies for different crops; wheat requires a cool time for sowing but a hot time for ripening, barley requires a cool, and oats a still cooler

¹ For other papers see C. A. Shull, *Bot. Gaz.*, 1911, 52, 453-477, and W. A. Cannon and E. E. Free, *Science*, 1917, 45, 178-180.

time throughout. It varies even for different varieties of the same crop; plant breeders are continually trying to evolve strains suited to particular ranges, *e.g.* wheats have been bred at Ottawa to ripen in the northern parts of Canada.

2. It affects the lengths of the periods of vegetative growth and of maturation and therefore causes certain modifications in the plant itself.

A long ripening period gives wheat a plump kernel with a low percentage of protein, while a short ripening period gives an increased protein content (Lawes and Gilbert in 1857, 166*c*).

Turnips in the south of England not only make less growth than in the north, but have a somewhat different composition. Oat straw in Scotland differs in composition from that in England, the translocation of material to the grain being apparently less complete.

3. The temperature at the time of ripening profoundly affects the germination capacity of the seed.¹

Light.

Although light is not a soil factor it nevertheless indirectly affects the soil by modifying the flora which, as we shall

¹ For a discussion of the physiological effects produced by temperature see — *Action de la Chaleur et du froid sur l'activité des êtres vivants*: par Georges Matisse. Paris (Larose), 1919.

Bull. Internat. Inst. Ag. Rome, 1917, **8**, 340.

Darwin, Francis, *On the growth of the fruit of "Cucurbita"* (*Annals of Botany*, 1893, **28**, 459-487).

Leitch, I., *Some experiments on the influence of the rate of growth of "Pisum sativum"* (*Ann. Botany*, 1916, **30**, 25-46).

Lehenbauer, P. A., *Growth of maize seedlings in relation to temperature* (*Physiol. Researches*, **1**, 247-288, 1914).

Lepeschkin, W. W., *Zur Erkenntnis der Einwirkung supramaximaler Temperaturen auf die Pflanze* (*Ber. Deutsch. Bot. Gesell.*, **30**, 703-714, 1912).

Maximow N. A., *Chemische Schutzmittel der Pflanzen gegen Erfrieren* (*Ber. Deutsch. Bot. Gesell.*, **30**, 52-65, 293-305, 504-916, 1912).

Groves, J. F., *Temperature and life duration of seeds* (*Bot. Gazette*, **63**, 169-189, 1917).

Livingstone, B. E., and Livingstone, Grace J., *Temperature Coefficients in Plant Geography and Climatology* (*Bot. Gazette*, 1913, **56**, 349-375. Abs. in *Journ. Ecol.*, 1914, **2**, 179).

subsequently see, largely determines the nature and amount of the organic matter of the soil. Tall vegetation keeps off light from the lower growing plants and more or less suppresses them. Thus on the Rothamsted grass plots clover is seriously reduced in amount by nitrate of soda which causes tall growing grasses to flourish: Lathyrus, on the other hand, in consequence of its tall growing habit is not adversely affected but grows vigorously. Numerous other instances are recorded in the *Journal of Ecology*.¹ The extreme case is seen in wood-land where there is very little undergrowth and where, therefore, organic matter has not accumulated in the soil. Adjacent pieces of land at Rothamsted, both untreated and differing only in the flora, showed the following differences in composition:—

| | Long Established. | | Established 40 Years. | |
|-----------------|---|--------------------------------|---|--------------------------------|
| | Open Land. Flora of Grass and Clover. | Wood-land. No Green Plants. | Open Land. Flora of Grass and Clover. | Wood land. No Green Plants. |
| Organic matter— | | | | |
| 0 - 9 ins. | 8.5 | 6.7 | 7.9 | 8.1 |
| 9 - 18 " | 4.8 | 4.8 | 6.7 | 5.2 |
| Nitrogen— | | | | |
| 0 - 9 ins. | 0.256 | 0.185 | 0.182 | 0.173 |
| 9 - 18 " | 0.097 | 0.093 | 0.084 | 0.081 |

One of the most effective ways of suppressing weeds is to grow a heavy crop which, in the farmer's language "smothers" them by excluding light and by exerting certain root effects.

Food.

The nutrition of plants is complicated by the fact that plants synthesise their own food from various substances taken out of the air and the soil. It is common in farmers' lectures to speak of these as the actual foods, but the student must be perfectly clear in his own mind that they are only the raw materials out of which the food is made. It is

¹ See e.g. E. Farrow, *Journ. Ecology*, 1916. 4.

convenient to make a distinction between the elements necessary in large quantities, and those of which mere traces suffice: the effect of the former can readily be demonstrated in water and sand cultures; the latter are more difficult to study, as traces are always present in the seed, and often also in the nutritive medium, or the vessel in which the plant is grown.

The substances needed in quantity are carbon dioxide, water, oxygen, and suitable compounds of nitrogen, phosphorus, sulphur, potassium, calcium, magnesium, and iron. Of these nitrogen, phosphorus, and potassium compounds are required in such large amounts that they usually have to be added to soils as artificial fertilisers in order to obtain maximum yields in agricultural practice. The other nutrient elements are generally present in air, in soils or in rain, in sufficient amounts to exert their full effect.

In addition to the above substances, small amounts of manganese and silicon are known to be beneficial: recent evidence suggests that others may be also. The list of elements of which traces only are needed has been much extended in an important investigation by Mazé (197), who includes boron, fluorine, iodine, chlorine, aluminium, and zinc. Evidence is steadily accumulating that these substances, in suitable traces, are beneficial to plant growth, as will be shown below.

Between nutritive effects and toxicity the margin appears to be narrow, and almost all the elements essential to plant nutrition are capable of producing toxic effects under other conditions. In the case of the major nutritive elements toxicity occurs only when a sufficiently large excess is present to alter considerably the osmotic relationships or the proper physiological balance of the nutrient medium: the transition from beneficial to harmful effects is very gradual and proceeds through the long inert stage shown in Fig. 7. In the case of elements of which only small amounts are needed the transition is much sharper: the limits are easily overstepped and toxic effects set in when the minute beneficial amount is exceeded.

Carbon.—It is generally assumed that plants derive all their carbon from the air, but the French investigators have

persistently held the view that some may come from the soil (p. 15). The physiological work has usually been done in water cultures. Knudson¹ finds that saccharose, glucose, maltose, and fructose are directly absorbed and utilised by green maize, Canada field pea, timothy, radish, vetch, etc., giving rise to a characteristic branched root system. While these substances do not occur in the soil other soluble carbon compounds are present, especially in glasshouse soils, and may exert important effects.

There is considerable evidence, however, that by far the larger portion of the carbon of the plant is taken up from the atmosphere and not from the soil, but the phenomena are not wholly independent of the soil. The amount of carbon dioxide in the atmosphere is subject to slight variations which may arise from variations in biochemical activity in the soil, and may be a factor of importance in crop production. Brown and Escombe (59*a*) found that the amount varied at Kew from 2.43 to 3.60² volumes per 10,000 volumes of air, the average being 2.94. Taking the month of July as an example, the average values were :—

| | | | | |
|--|-------|-------|-------|-------|
| | 1898. | 1899. | 1900. | 1901. |
| CO ₂ in 10,000 volumes of air . | 2.83 | 2.88 | 2.86 | 3.11 |

It is probable that the plant as a whole would respond to variations of this order, making greater or less growth as the amount of carbon dioxide rises or falls.³

Nitrogen.—Of all the nitrogen compounds yet investigated nitrates are the best, and, in natural conditions, probably the only nitrogenous food for non-leguminous plants. The seedling, still drawing its sustenance from the seed, lives on other compounds : H. T. Brown (59*b*) found that asparagine was the most effective nutrient for the detached embryo of barley, followed by other relatively simple substances like nitrates, glutamic and aspartic acids, ammonium sulphate, etc., the more complex substances being less useful. The experimental

¹ *Cornell Repts.* (Ithaca, N.Y.), 1917, 747-813 (Memoir 9 of 1916).

² Only on one occasion was so high a number obtained.

³ See E. Demoussy (83) and Otto Warburg, *Biochem. Zeitsch.*, 1919, 100, 230.

study of the nitrogen nutrition of adult plants is complicated by the difficulty of growing plants under sterile conditions in which the decompositions effected by bacteria are obviated; much of the earlier work is vitiated by this circumstance. Later work has satisfactorily shown that ammonia is readily assimilated from solutions of ammonium sulphate if the concentration is not too high; but even 0.1 per cent. was found injurious by Mazé (196). Krüger (1956b) concludes that ammonium sulphate is less beneficial than sodium nitrate for mangolds; both compounds are equally useful for oats, barley, and mustard, while ammonium sulphate is better for potatoes. Brigham¹ maintains that maize also thrives better on ammonium sulphate than on sodium nitrate. Hutchinson and Miller (190a) found that peas assimilate nitrates and ammonium salts equally well, while wheat showed a decided preference for nitrates. Söderbaum² found that the effect varied with the salt: ammonium phosphate was more beneficial than the sulphate, while the chloride was harmful.

An interesting attempt has been made by Prianichnikow (1929b) to elucidate the phenomena of ammonia assimilation by plants. He supposes that the ammonia taken up by the roots is transformed in the plant into asparagine, which is then converted into protein. Some plants, *e.g.* barley, maize, pumpkin, etc., readily take up ammonia and effect the conversion; others, such as peas and vetches, do so only in presence of calcium carbonate; whilst others, such as lupin, will not normally take up ammonia at all. He suggests that this difference is due to the different quantities of carbohydrates at the disposal of the plant; by increasing or diminishing the amount of carbohydrate it is possible to pass from one type of assimilation to another. In a state of inanition the power of forming asparagine is lost; with plentiful supply of carbohydrate, on the other hand, even plants of the lupin type could absorb ammonia and convert it into asparagine. Asparagine can accumulate in the plant without detriment, and can be built

¹ *Soil Sci.*, 1917, 3, 155.

² *Kungl. Landt. Handlingar*, 1917, 56, 537-561.

up into protein when sufficient carbohydrate is present. This accumulation would account for the fact on which all experimenters agree, that plants fed on ammonium salts contain a higher percentage of nitrogen than those fed on nitrates (Table XIV.).

TABLE XIV.—PERCENTAGE OF NITROGEN IN DRY MATTER OF PLANTS.

| | Fed on Nitrates. | Fed on Ammonium Salts. | Observer. |
|-------------|------------------|------------------------|------------------------------|
| Maize . . . | 3.17 | 3.43 | Mazé (196) |
| Mustard . . | 2.87 | 3.48 | Krüger (156b) |
| Oats . . . | 1.80 | 2.05 | " " |
| Wheat . . . | 1.91 | 2.17 | Hutchinson and Miller (140a) |

Nitrites are also assimilated so long as the solution is not too concentrated or too acid.¹

In spite of a considerable amount of work it is not known whether nitrogen compounds other than nitrates and ammonia are assimilated by plants. That many other compounds serve as nitrogen nutrients, even without the intervention of bacteria, seems to be certain (140b), but it has never been shown whether assimilation of the compound as a whole takes place, or whether there is decomposition at the surface of the root. Many of the supposed assimilated compounds are as a matter of fact more or less easily hydrolysable, or otherwise decomposable, with formation of ammonia, and the decomposition will obviously proceed as fast as the ammonia is removed by the plant. Two factors that determine how far a given compound serves as a nitrogen nutrient are: (1) the ease with which it splits off ammonia, (2) the effect on the plant of the other decomposition products: if these happen to be toxic the whole process stops as soon as they have sufficiently accumulated.

The normal nitrogenous food of plants is, however, a nitrate, and there is a close connection between the amount supplied and the amount of plant growth, which is well shown in Hellriegel and Wilfarth's (130c) experiments (Table XV.).

¹ See Perciabosco and Rosso, *Staz. Speriment. Agrar. ital.*, 1909, xlii., 5.

TABLE XV.—EFFECT OF NITROGENOUS FOOD SUPPLY ON THE GROWTH OF BARLEY IN SAND CULTURES. HELLRIEGEL.

| | | | | | | |
|--|------|-------|--------|--------|--------|--------|
| Milligrams of nitrogen supplied | 0 | 56 | 112 | 168 | 280 | 420 |
| Dry matter in crop, grams | 7.42 | 48.56 | 108.03 | 175.28 | 212.89 | 287.27 |
| Increased yield for each extra 56 mgms. nitrogen | — | 4.114 | 5.947 | 6.725 | 1.880 | 2.975 |
| Grain, per cent. of dry matter in crop | 11.9 | 37.9 | 38 | 42.6 | 38.6 | 43.4 |
| Weight of one grain, mgms. | 19.5 | 30 | 33 | 32 | 21 | 30 |

The figures are plotted in Fig 10. Similar results are obtained on the field plots at Rothamsted (Table XVI.).

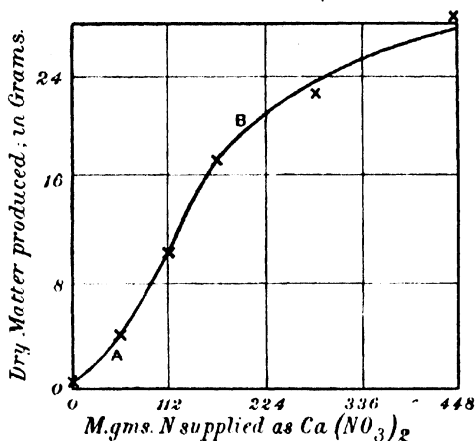


FIG. 10.—Effect of nitrogenous food supply on the growth of barley. (Hellriegel.)

TABLE XVI.—BROADBALK WHEATFIELD, AVERAGE YIELDS, FIFTY-SIX YEARS, 1852-1907.

| | Plot 5. | Plot 6. | Plot 7. | Plot 8. |
|---|---------|---------|---------|---------|
| Nitrogen supplied in manure, lb. per acre | 0 | 43 | 86 | 129 |
| Total produce (straw and grain), lb. per acre | 2315 | 3948 | 5833 | 7005 |
| Increase for each 43 lb. nitrogen | — | 1633 | 1885 | 1172 |

The increasing effects produced up to a certain point by successive increments of nitrogen may be due to the circumstance that the additional nitrate not only increases the con-

centration of nitrogenous food in the soil, but also increases the amount of root, *i.e.* of absorbing surface, and of leaf, *i.e.* assimilating surface. The process thus resembles autocatalysis, where one of the products of the reaction acts as a catalyser and hastens the reaction. The increase does not go on indefinitely because some limiting factor steps in.

The effect of nitrogen supply on the grain is very marked. In Table XV, it is seen that the grain formed, when nitrogenous food is wholly withheld, is only two-thirds of the normal weight per individual. The first addition of nitrate causes a marked rise in the weight per grain and the proportion of grain to total produce, but successive additions cause no further rise. Indeed other experiments prove that excess of nitrogenous food causes the proportion of grain to fall off somewhat. The leaf and the general character of growth are affected to a much greater extent. Nitrogen starvation causes yellowing of the leaf, especially in cold spring weather, absence of growth, and a poor starved appearance generally: a moderate supply of nitrogen leads to more rapid growth, very useful in cold weather or in case of attacks by insect pests. Abundance of nitrogen, on the other hand, leads to the development of large dark green leaves which are often crinkled, and usually soft, sappy, and liable to insect and fungoid pests (apparently because of the thinning of the walls and some change in composition of the sap) and to retarded ripening: the effects resemble those produced by abundant water supply. A series of plants receiving varying amounts of nitrate are thus at somewhat different stages of their development at any given time, even though they were all sown on the same day, those supplied with large quantities of nitrate being less advanced than the rest. If they could all be kept under constant conditions till they had ripened this difference might finally disappear, but in crop production it is not possible much to delay the harvest owing to the fear of damage by autumn frosts, so that the retardation is of great practical importance. Seed crops like barley that are cut dead ripe are not supplied with much nitrate, but oats, which are cut before being quite

ripe, can receive larger quantities. All cereal crops, however, produce too much straw if the nitrate supply is excessive, and the straw does not commonly stand up well, but is beaten down or "lodged" by wind and rain. Swede and potato crops also produce more leaf, but not proportionately more root or tuber, as the nitrogen supply increases; no doubt the increased root would follow, but the whole process is sooner or later stopped by the advancing season—the increased root does, in fact, follow in the case of the late-growing mangold. Tomatoes, again, produce too much leaf and too little fruit if they receive excess of nitrate. At the Cheshunt Experiment Station¹ the omission of nitrogen compounds from the fertiliser mixture has caused the yield of fruit to increase 11 per cent. With the variety Comet the following quantities of fruit have been obtained:—

| | Lb. per plant. | | | | Tons per acre. | | | | Relative Weights. Average, 1916-1919. |
|----------------------|----------------|-------|-------|-------|----------------|-------|-------|-------|---|
| | 1916. | 1917. | 1918. | 1919. | 1916. | 1917. | 1918. | 1919. | |
| Complete artificials | 4·9 | 5·11 | 3·32 | 5·57 | 38·7 | 35·8 | 25·8 | 42·2 | 100 |
| No nitrogen . . . | 5·7 | 5·60 | 3·62 | 5·98 | 45·0 | 39·2 | 28·2 | 47·4 | 111 |

On the other hand, crops grown solely for the sake of their leaves are wholly improved by increased nitrate supply: growers of cabbages have learned that they can not only improve the size of their crops by judicious applications of nitrates, but they can also impart the tenderness and bright green colour desired by purchasers. Unfortunately the softness of the tissues prevents the cabbage standing the rough handling of the market. These qualitative differences are of great importance in agriculture and horticulture.

Three cases are illustrated in Table XVII.; as the nitrogen supply is increased wheat shows increases in straw greater than those in grain; white turnips show increases in leaf greater than those in root, but mangolds show substantially the same increase both in leaf and root, because their growing

¹ Annual Reports for 1917 *et seq.*

period is so much longer than that of the other crops, continuing until the end of October.

TABLE XVII.—EFFECT OF VARYING SUPPLY OF NITROGENOUS MANURE ON THE GROWTH OF CROPS, ROTHAMSTED.

| Nitrogen in Manure, lb. per acre. | Wheat 1000 lb. per acre (1852-1864). | | Nitrogen in Manure, lb. per acre. | White Turnips, 1000 lb. per acre (1845-1848). | | Nitrogen in Manure, lb. per acre. | Mangolds, 1000 lb. per acre. (1906-1910). | |
|-----------------------------------|--------------------------------------|--------|-----------------------------------|---|---------|-----------------------------------|---|---------|
| | Grain. | Straw. | | Roots. | Leaves. | | Roots. | Leaves. |
| none | 1'06 | 1'86 | none | 18'37 | 6'05 | none | 11'84 | 2'55 |
| 43 | 1'68 | 3'03 | 47 | 22'18 | 9'63 | 86 | 40'12 | 8'51 |
| 86 | 2'18 | 4'28 | 137 | 22'90 | 13'78 | 134 | 65'67 | 13'88 |
| 129 | 2'27 | 4'78 | — | — | — | — | — | — |
| 172 | 2'29 | 5'22 | — | — | — | — | — | — |

The actual increase of growth brought about by successive increments of nitrogenous food depends on the amount of water and other nutrients, on the temperature, and so on; any of these may act as limiting factors. Table XVIII. shows the crops obtained on some of the Rothamsted mangold plots; in one case the supply of potassium is so small that it becomes the limiting factor, in the other sufficient potassium is supplied.

TABLE XVIII.—INFLUENCE OF POTASSIUM SALTS ON THE ACTION OF NITROGENOUS MANURES. ROTHAMSTED.

| | Average Weights, Mangolds, 1906-1910. | | | | | |
|---|---------------------------------------|-----------------|------------------|----------------------------|-----------------|------------------|
| | Roots, 1000 lb. per acre. | | | Leaves, 1000 lb. per acre. | | |
| Insufficient potassium (Series 5) | 11'97 | 14'68 | 18'62 | 2'59 | 7'25 | 7'75 |
| Sufficient potassium (Series 4) | 11'84 | 40'12 | 65'67 | 2'55 | 8'51 | 13'88 |
| Nitrogen supplied in manure, lb. per acre | — | 86 ¹ | 184 ² | — | 86 ¹ | 184 ² |

The effect of varying water supply is more conveniently studied in pot experiments than in the field, since any comparison between yields in wet and dry seasons is complicated

¹ From 400 lb. ammonium salts.

² From 400 lb. ammonium salts and 200 lb. rape cake.

by the great differences in temperature conditions. Tucker and von Seelhorst's experiments have already been described (pp. 38 and 44).

From the practical point of view the important result is that a given increase in the food supply may produce no increased growth, small increase, or a larger increase, according to the extent of the water supply.

Phosphorus.—Phosphates are by far the most efficient phosphorus foods known for plants. The relationship between phosphorus supply and growth has been measured by E. A. Mitscherlich (p. 33) in a series of experiments on oats grown in sand with each of the three calcium phosphates. For equal weights of the three salts the relative efficiencies corresponded with the basicity; for equal weights of P_2O_5 , however, the values were 2.66 : 2.31 : 1.65. This was in sand cultures; in soils different efficiencies were found: thus for the monophosphate the values were:—

| Sand. | Soil 1. | Soil 2. | Soil 3. |
|-------|---------|---------|---------|
| 2.66 | 1.80 | 1.74 | 2.40 |

The effect of a phosphate on the crop is twofold. In the early stages of growth it promotes root formation in a remarkable way. So long ago as 1847 Lawes (161) wrote: "Whether or not superphosphate of lime owes much of its effect to its chemical actions in the soil, it is certainly true that it causes a much enhanced development of the *under-ground* collective apparatus of the plant, especially of *lateral* and *fibrous* root, distributing a complete network to a considerable distance around the plant, and throwing innumerable mouths to the surface". Dressings of phosphates are particularly effective wherever greater root development is required than the soil conditions normally bring about. They are invaluable on clay soils, where roots do not naturally form well, but, on the other hand, they are less needed on sands, because great root growth takes place on these soils in any case. They are used for all root crops like swedes, turnips, potatoes, and mangolds; in their absence swedes and turnip roots will not swell but remain permanently dwarfed like



No manure.

Superphosphate and potassic fertiliser.

Nitrogen superphosphate and potassic fertiliser.

FIG. 11.—Swedes from Agdell field. Broadbald's; unmanured; superphosphates and potassic fertilisers; and complete fertiliser, Agdell and Calloway.

radishes (Fig. 11 shows one of Lawes and Gilbert's photographs): the introduction of superphosphate as a fertiliser revolutionised agriculture on some of the heavier soils by allowing better growth of these crops. Phosphates are needed also for shallow-rooted crops with a short period of growth, like barley. Further, they are beneficial wherever drought is likely to set in, because they induce the young roots to grow rapidly into the moister layers of soil below the surface; probably, as Hall has suggested, this explains the marked effect of superphosphate on wheat in the dry regions of Australia.

Later on in the life of the plant phosphates hasten the ripening processes, thus producing the same effect as a deficiency of water, but to a less extent; for this reason they are applied to the wheat crop in some of the northern districts of England, and the oat crop in the west, to bring on the harvest a few days earlier and obviate risk of loss by bad weather. The northern limit of growth of several crops may in like manner be extended. This ripening effect is well shown on the barley plots at Rothamsted: crops receiving phosphates are golden yellow in colour while the others are still green.

But these effects, important as they are, are nothing like as striking as those shown by nitrogen compounds. There is no obvious change in the appearance of the plant announcing deficiency or excess of phosphate¹ like those changes showing nitrogen starvation or excess; the hastening of maturity is seen only when there is a control plot unsupplied with phosphates: it leads to no increase in the proportion of grain borne by the plant. On the Rothamsted plots supplied with nitrogen and potassium compounds, but no phosphate, the grain formed 44·9 per cent. of the total produce during the first ten years of the experiment (1852-1861), and almost exactly the same proportion (44·7 per cent.) during the fifth ten years (1892-1901) when phosphate starvation was very

¹ Barley grown in water cultures without phosphorus compounds acquires a red colour in the stem, but this is not commonly seen in the field.

pronounced; it fell a little to 41.3 per cent. in the sixth ten years (1902-1911), but rose to 46.8 per cent. in the period 1913-1919. Even in sand cultures the difference is not very marked: Hellriegel (130*d*) grew barley with varying supplies of phosphate with results given in Table XIX. In absence of phosphate no grain was formed; when a little was added grain formation proceeded normally, and the resulting grain was nearly full weight per individual; as the phosphate supply increased the percentage of grain increased, but soon reached a maximum beyond which it would not go.

TABLE XIX.—EFFECT OF VARYING PHOSPHATE SUPPLY ON THE GROWTH OF BARLEY IN SAND CULTURES. HELLRIEGEL (130*d*).

| | | | | | | | | | |
|--|-------|-------|--------|--------|--------|--------|--------|--------|--------------------|
| Weight of P_2O_5 supplied, mgms. per pot . . . | 0 | 14.2 | 28.4 | 56.8 | 85.2 | 113.6 | 142 | 213 | 284 |
| Weight of dry matter in crop, grams per pot . . | 1.856 | 8.254 | 12.613 | 19.505 | 19.549 | 20.195 | 18.667 | 17.785 | 31.30 ^a |
| Grain per cent. of dry matter . . . | — | 22.4 | 31.8 | 38.4 | 41.6 | 43.8 | 41.3 | 40.1 | 43.4 |
| Weight of one grain, mgms. . . | — | 27 | 29 | 38 | 34 | 41 | 38 | 30 | 34 |

It is in the total growth of straw and of grain that the effect of phosphate is manifested as shown in Table XX.

The Rothamsted results are plotted in Fig. 12. The effect of phosphate starvation shows itself in depressing the yield of straw and of grain, the straw being the first to suffer. Potash starvation takes longer to set in, not because potassium is less necessary but because the soil contains a larger quantity; it also affects the straw first. Nitrogen starvation sets in at once, rapidly bringing both grain and straw down to a very low level.

It is difficult to get behind these effects and ascertain their causes. The function of phosphoric acid in the cell is not easy to discover; even when the problem is reduced to its simplest state by experimenting with *Spirogyra* in culture solutions little more has been ascertained than that phosphates are essential for mitotic cell division, doubtless because phos-

phorus is a constituent of the nucleus, and also for the normal transformations of starch. Loew (1808) found that fat and albumin accumulated in absence of phosphates, but the colour was yellow and there was no cell division; as soon as a trace of potassium phosphate was added, however, energetic cell division took place. Reed (236) showed that starch was formed in absence of phosphorus, but did not change to sugars; erythroextrin was formed instead and also cellulose.

TABLE XX.—RESULTS OF WITHHOLDING PHOSPHATES, POTASSIUM COMPOUNDS, AND NITROGEN COMPOUNDS FROM BARLEY. HOOS FIELD EXPERIMENTS, ROTHAMSTED.

| Treat. | Yield of Grain, 1000 lb. per acre. | | | | | | | |
|--|------------------------------------|----------------------|-----------------------|-----------------------|-----------------------|-------------------------|-----------------------|----------------------|
| | 5 years, 1852-56. | 5 years, 1857-61. | 10 years, 1862-71. | 10 years, 1872-81. | 10 years, 1882-91. | 10 years, 1892-1901. | 10 years, 1902-11. | 7 years, 1913-19. |
| 7 Dung | 2'31 | 2'78 | 3'00 | 2'88 | 2'66 | 2'56 | 2'50 | 2'35 |
| 4 Complete manure (salts of NH_4 , K and P) | 2'47 | 2'71 | 2'67 | 2'34 | 2'24 | 2'02 | 2'25 | 2'06 |
| 3 No phosphates | 2'27 | 1'71 | 1'99 | 1'68 | 1'38 | 1'26 | 1'23 | 1'38 |
| 2 No potassium | 2'42 | 2'70 | 2'76 | 2'29 | 2'01 | 1'63 | 1'81 | 1'88 |
| 1 No nitrogen | 1'86 | 1'57 | 1'39 | 1'98 | 1'92 | 1'74 | 1'94 | 1'31 |

| Treat. | Yield of Straw, 1000 lb. per acre. | | | | | | | |
|--|------------------------------------|----------------------|-----------------------|-----------------------|-----------------------|-------------------------|-----------------------|----------------------|
| | 5 years, 1852-56. | 5 years, 1857-61. | 10 years, 1862-71. | 10 years, 1872-81. | 10 years, 1882-91. | 10 years, 1892-1901. | 10 years, 1902-11. | 7 years, 1913-19. |
| 7 Dung | 2'82 | 3'15 | 3'35 | 3'37 | 3'28 | 3'35 | 3'54 | 2'73 |
| 4 Complete manure (salts of NH_4 , K and P) | 3'29 | 3'17 | 3'14 | 2'63 | 2'61 | 2'36 | 2'83 | 2'17 |
| 3 No phosphates | 2'86 | 2'03 | 2'20 | 1'75 | 1'64 | 1'56 | 1'75 | 1'57 |
| 2 No potassium | 3'21 | 3'03 | 3'07 | 2'30 | 2'20 | 1'90 | 2'16 | 1'78 |
| 1 No nitrogen | 2'03 | 1'58 | 1'42 | 1'95 | 1'94 | 1'90 | 1'39 | 1'46 |

The effects of phosphates in raising the quality and feeding value of the crop are very great. The most nutritious pastures in England and the best dairy pastures in France are those richest in phosphates. Soils deficient in phosphates are nearly always unsatisfactory. Paturel¹ has also shown that the best

¹ Bull. Soc. Nat. Agric., 1911, p. 977.

wines contain most P_2O_5 (about 0.3 grm. per litre), the second and lower qualities containing successively less. Further, when the vintages for different years were arranged in order of their P_2O_5 content a list was obtained almost identical with the order assigned by the wine merchants. Davis (78a) has emphasised the importance of phosphate supply for the indigo crop.

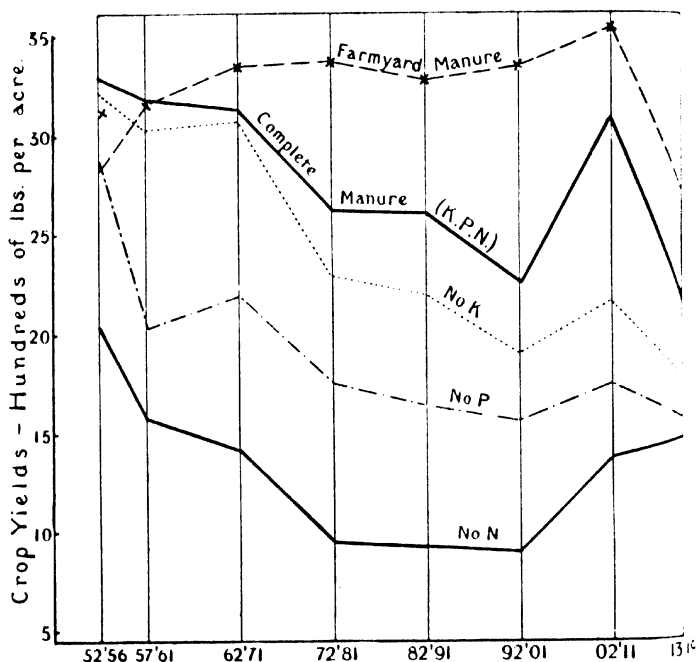


FIG. 12A.—Effect on yield of grain of withholding various nutrients from barley. (Hoos field, Rothamsted.)

The close connection between cell division and phosphate supply may account for the large amount of phosphorus compounds stored up in the seed for the use of the young plant, and also the relatively large amounts of phosphate taken from the soil during the early life of the plant.

Potassium.—Hellriegel has shown (Table IV., p. 31) that

equivalent amounts of the soluble compounds of potassium have practically all the same nutritive value.

The effect of potassium compounds is more localised than that of phosphates, so that potash starvation can be more readily detected. The colour of the leaf becomes abnormal; the potash-starved grass plots at Rothamsted have a poor, dull colour, as also have the mangold plots; the leaves also

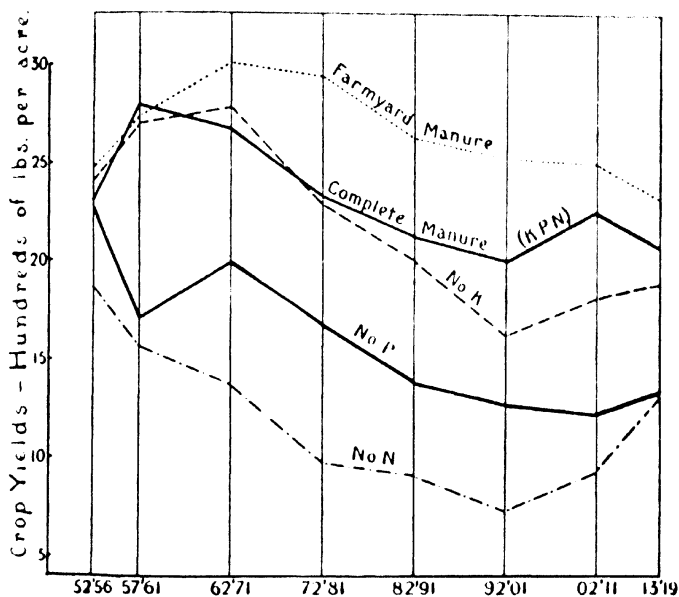


FIG. 12B.—Effect on yield of straw of withholding various nutrients from barley. (Hoos field, Rothamsted.)

tend to die early at the tips. The stem is weaker so that the plant does not stand up well; this is apparently a turgidity effect, although anatomical differences were observed by Miss O. N. Purvis.¹ The most striking effect, however, is the loss of efficiency in making starch, pointed out long ago by Nobbe (215a); either photosynthesis or translocation—it is not yet clear which—is so dependent on potassium salts that

¹ *Journ. Agric. Sci.*, 1919, 9, 360.

the whole process comes abruptly to an end without them. Mangolds, sugar beets, potatoes, and other sugar- and starch-forming crops reduce their production of sugar with decreasing potassium supply even before the leaf area has been diminished. Thus, in the mangold experiments of Table XVIII. (p. 63), 7255 lb. of leaf give rise to 14,684 lb. of root where potash food is deficient, while very little more leaf, 8508 lb., give rise to nearly three times as much root, 40,128 lb., where more potassium salts are supplied. The harmful effect of potash starvation on carbohydrate production does not seem to be the result of a pathological condition of the chloroplastids. Reed found that they remained normal for two months and even increased in numbers in potash-starved algæ.

A second effect is on the formation of grain; unlike phosphates and nitrates, potassium compounds have a very marked effect on the weight of the individual grains, as may be seen by comparing Table XXI. with the corresponding Tables XV. (p. 60) and XIX. (p. 66); indeed, to withhold potash is the surest way of producing stunted grain. At Rothamsted the average weights per bushel of wheat for the ten years 1910-1919 were:—

| No Manure. Plot 3. | Farmyard Manure. Plot 2. | Complete Artificials. Plot 7. | Artificials without Nitrogen. Plot 5. | Artificials without Potash. Plot 11. |
|-----------------------|--------------------------------|-------------------------------------|---|--|
| 61.5 | 62.3 | 62.2 | 61.8 | 60.7 |

TABLE XXI.—EFFECT OF POTASSIUM SALTS ON THE DEVELOPMENT OF BARLEY.
HELLRIEGEL (130d).

| K ₂ O supplied, mgs. | 0 | 23.5 | 47 | 70.5 | 94 | 188 | 282 |
|---------------------------------|-------|-------|-------|--------|--------|--------|--------|
| Dry matter in crop, grams | 2.271 | 5.414 | 9.024 | 11.636 | 15.302 | 20.946 | 29.766 |
| Grain, per cent of dry matter | — | 4.8 | 21.5 | 27.2 | 30.1 | 38.5 | 42.7 |
| Weight of one grain, mgs. | — | 5 | 9.5 | 13 | 17 | 26 | 34 |

Lastly, the vigour and healthiness of the plant are very dependent on the potassium supply; potash-starved plants are the first to suffer in a bad season, or to succumb to

disease. The Broadbalk wheat plots receiving potassium salts give conspicuously better results than the others whenever the year is unfavourable to plant growth; taking the yield on the unmanured plot as an index of the character of the season, we obtain the following results for a series of good and of bad years respectively:—

TABLE XXII.—YIELD OF WHEAT IN THOUSAND POUNDS PER ACRE.
ROTHAMSTED.

| | Plot No. | In Nine Bad Seasons. ¹ | | In Nine Good Seasons. ¹ | |
|-----------------------------------|----------|-----------------------------------|--------|------------------------------------|--------|
| | | Grain. | Straw. | Grain. | Straw. |
| Unmanured | 4 | ·55 | ·87 | ·88 | 1·08 |
| Insufficient potash | 11 | 1·06 | 1·80 | 1·51 | 2·20 |
| Sufficient potash | 13 | 1·70 | 3·02 | 1·98 | 3·16 |
| Percentage increase due to potash | — | 60·3 | 62·3 | 31·1 | 43·6 |

In the bad years the average rainfall was 32·55 inches (harvest years, September-August), while in the good years it was 27·10 inches; the badness of the season may be connected with the high rainfall and corresponding low temperature. Similar results are obtained, however, if other unfavourable conditions set in.

The improvement in healthiness is well exemplified by the power of resisting disease. At Rothamsted the potash-starved wheat and mangolds are liable to be attacked by disease, especially where there is excess of nitrogen, while the surrounding plots, equally liable to infection, remain healthy. Flax growers in the north of Ireland have found that potassic fertilisers increase the resistance of the plant to the attacks of the wilt organism.

At the Cheshunt Experimental Station liberal treatment with potassic fertilisers makes the tomato plant more resistant

¹ The bad years were 1867, '71, '72, '75, '76, '77, '79, '86, '88; the good years were 1868, '69, '70, '81, '83, '85, '87, '89, '91.

to the bacterial stripe disease: the numbers of plants affected out of a total of 120 in each plot were:—¹

| | Complete Fertiliser. | No Potassic Fertiliser. |
|----------------------------|----------------------|-------------------------|
| Var. Comet | 40 | 78 |
| Var. Kondine Red | 13 | 33 |

Potassic fertilisers often afford the simplest method of dealing with fungoid diseases and they are usually more effective than other fertilisers under glass.

Next to the sugar-producing plants, the leguminosæ seem to stand most in need of potassium salts. The potash-starved grass plots at Rothamsted contain notably less clover than those fully manured, the actual depression fluctuating according to the season. Some of the weeds, especially the sorrel, require a good supply of potash.

There is some controversy as to whether potassium plays any important part in protein synthesis in plants.²

In absence of potassium salts mitotic cell division does not go to completion; Reed observed that the cell and nucleus both elongate, but actual division does not occur (236).

It is not at present possible to say whether all these phenomena are different manifestations of one and the same specific action of potassium in the plant, or whether there are several different causes at work. Zwaardemaker³ puts forward the interesting suggestion that the potassium ion (which is somewhat radioactive) may be replaced by any other radioactive element, light or heavy, or by free radioactive radiation, provided the doses are equi-radioactive.

Sodium does not appear to be essential even to salt marsh plants, although *salicornia* grew better in presence of salt than in its absence.⁴ It can partially, but not completely,

¹ S. G. Paine and W. F. Bewley, *Annals of Applied Biology*, 1919, 6, 185.

² J. Stoklasa, *Biochem. Zeitsch.*, 1917, 82, 310-323; T. Weevers, *ibid.*, 1917, 78, 354.

³ *J. Physiol.*, 1920, 53, 273.

⁴ A. C. Halket, *Annals of Botany*, 1915, 29, 143-154.

replace potassium as a plant nutrient; it thus delays the setting in of potash starvation, but will not keep it off altogether. Hellriegel (130*d*) found that sodium salts always gave increases in crop even when potassium salts were present in quantity.

TABLE XXIII.—EFFECT OF SODIUM SALTS WITH SMALL AND WITH LARGE AMOUNTS OF POTASSIUM SALTS ON THE GROWTH OF BARLEY. HELLRIEGEL (130*d*).

| K ₂ O supplied, mgs. | 0 | 94 | 188 | 282 | 376 |
|--|-------|--------|--------|--------|--------|
| Dry matter produced when sodium salts added | 4'925 | 23'019 | 32'278 | 36'535 | 38'270 |
| Dry matter produced when no sodium salts added | 2'058 | 15'638 | 29'724 | 34'897 | 36'281 |
| Difference due to sodium salts | 2'267 | 7'381 | 2'554 | 1'638 | 1'989 |

Breazeale (51*b*) has more recently obtained similar results in water cultures. It is well ascertained in farming practice that sodium salts can be used with great effect as manures wherever there is any deficiency of potash in the soil.¹

J. A. Voelcker (290) has made the interesting observation that sodium hydrate and sodium carbonate, unlike most other salts, cause an increase in the percentage of nitrogen in the wheat grain, besides increasing the yield of crop. The sulphate and the chloride increased the crop, but beyond a relatively low concentration limit further increases in amount of sodium chloride proved toxic.

Lithium salts, on the other hand, have a toxic action on plants. Gaunersdorper's older experiments² have been confirmed by J. A. Voelcker (290, 1912), who found that amounts of the chloride, sulphate, or nitrate, corresponding to .003 per cent. of the metal were distinctly injurious to wheat;

¹For fuller details see Krüger, *Zeitschr. Ver. Deut. Zuckerindus.*, 1914, 694-702; B. Schulze, *Beitrag zur Frage der Düngung mit Natronsalzen* (*Landw. Versuchs-Stat.*, 1913, 79-80, 431, and 1915, 86, 323-330); E. J. Russell, *Journ. Bd. Agric.*, 1915, 22, 393-406.

²*Landw. Versuchs-Stat.*, 1887, 34, 171-206.

smaller amounts, however, appeared to cause an increased growth.

Cæsium salts are less harmful (290).

Calcium is an essential plant food, the function of which was first carefully studied by von Raumer (234), but has not yet been satisfactorily cleared up. Little has been inferred from the fact that, like potassium, it occurs more in the leaf than in the seed. It certainly gives tone and vigour to the plant; gypsum is used in alkali regions to counteract the harmful effects of excessive amounts of saline matter in the soil. It also appears to stimulate root production: if calcium is withheld from water cultures the size of the root is much reduced. Maquenne and Demoussy¹ show that the amount present in the seed of the pea is insufficient for root development, which therefore ceased on the third or fourth day of germination in pure water. Addition even of traces of calcium sulphate was followed by further root growth: 0.01 mg. of calcium sulphate per seed, representing an addition of calcium equal to 1/40,000 the weight of the dry seed, led to formation of root hairs and a 40 per cent. increase in root length.

The close relationship between calcium and nitrogen content suggests that the calcium may be associated with protein metabolism, perhaps combining with the acids to which such metabolism gives rise. Plants fall into two groups so far as calcium is concerned:—

(a) Those (including calcifuges) with low content of calcium and low calcium-nitrogen ratio; (b) those (including calcicolous plants) in which these quantities are high.²

Barium and *strontium* cannot replace calcium in the nutrition of plants. McHague (187) has shown that the carbonates are toxic, though in the presence of calcium carbonate they cause an increase in plant growth, strontium being more effective than barium. In Voelcker's experiments (290) the addition to the soil of even 0.1 per cent. of strontium sulphate, hydrate, or carbonate was without effect, but the

¹ *Compt. Rend.*, 1917, **164**, 979-985; and **165**, 45-51.

² F. W. Parker and E. Truog (*Soil Sci.*, 1920, **10**, 49).

chloride was distinctly toxic. In Loew's experiments on algæ (180c) strontium salts injuriously affected the chlorophyll bodies, causing loss of starch-making power and finally death.

Magnesium, like phosphorus, finally moves to the seed, and is thus in contrast with calcium and potassium, which remain behind in the leaf or the straw. Willstätter has shown (310) chlorophyll to be a magnesium compound, an observation that accounts for the unhealthy condition of the chlorophyll bodies, and the final etiolation of magnesium-starved plants. Further, magnesium seems to be necessary for the formation of oil, the globules being absent from algæ growing in solutions free from magnesium salts; oil seeds are richer in magnesium than starch seeds. An excess of magnesium salts produces harmful effects which, as we shall see (p. 78), can be lessened by addition of calcium salts; Loew indeed considers (180a) that plants require a definite $\frac{\text{CaO}}{\text{MgO}}$ ratio in their food, but neither Gössel¹ nor Lemmermann² could obtain evidence of any such necessity.

In J. A. Voelcker's experiments³ magnesium oxide, carbonate, and chloride had, like sodium hydroxide, the unusual effect of causing an increase in the nitrogen content of the wheat grain. The sulphate did not act in this way, although in suitable small amounts it caused increases in yield of grain and of straw. The chloride proved toxic at higher concentrations.

Aluminium compounds have been found beneficial by Stoklasa.⁴

Iron.—For some reason difficult to explain the formation of chlorophyll is absolutely dependent on the presence of a trace of some ferric salt, although iron does not enter into the composition of chlorophyll. So little is wanted that iron salts never need be used as manures, excepting for water or sand cultures.

¹ *Bied. Zentr.*, 1904, xxxiii., 226.

² *Landw. Jahrbuch*, 1911, xl., 175 and 255.

³ *J. Roy. Agric. Soc.*, 1915, 76, 354; 1916, 77, 260.

⁴ *Biochem. Zentsch.*, 1918, 91, 137.

Manganese is considered by Bertrand to be a constituent of oxidases, and, therefore, necessary to the plant; minute traces only are required, larger quantities being harmful. Dr. Brenchley's water cultures (54*a*) show that barley benefits by small doses of manganese salts, and a number of field experiments in Japan and in Italy¹ have indicated some manurial value. Bertrand regards manganese salts as "engrais complémentaires" (35). Field trials at Rothamsted, however, gave negative results.

Chlorine does not appear to be necessary to the plant in large quantity; indeed, Knop grew even the halophytes without it. Mazé finds that small amounts are necessary, which, however, would not need to be added in manure, as rainwater invariably contains chlorides: at Rothamsted the amount of chlorine brought down per acre averages 16 lb. per annum, the annual fluctuations varying with the rainfall between 10.3 and 24.4 lb.² Voelcker finds that, on the whole, chlorides are more toxic than sulphates at equivalent concentrations (290).

In small quantities both *fluorine* and *iodine* appear to increase plant growth: this was first shown in Japan by Loew (180*c*) and Suzuki (277*a*): it is also accepted in France by Mazé (197). Gautier and Clausmann (102) go even further and claim that a dressing of 5 kgms. of amorphous calcium fluoride per acre was followed by increases in cereal crops of 5 to 18 per cent., and sometimes considerably more in the case of root crops.

Sulphur is an essential food constituent, and occurs in plants, especially in cabbages and swedes, to a greater extent than is usually recognised, the older analytical methods giving low results (Hart and Peterson (127), Peterson (223)). Sulphates are present in rain and in soil, but further additions in

¹ The Japanese experiments are recorded in the *Bull. Coll. Agric.*, Tokyo, 1906 *et seq.* (210), and the Italian experiments in the *Studi e Ricerche di Chimica Agraria*, Pisa, 1906-8; pot experiments have also been made by J. A. Voelcker at the Woburn Experiment Station (*Journ. Roy. Ag. Soc.*, 1903, 64, 348-359). See also E. P. Deatrick, *Cornell Mem.*, 1919, 19, 371.

² E. J. Russell and E. H. Richards, *Journ. Ag. Sci.*, 1919, 9, 309.

manure were found by Bogdanow to be helpful.¹ Dymond (92) showed that sulphates increased the yield of heavy crops rich in protein, although they were not needed for cereals or permanent pastures. A number of recent investigations in the United States by Pitz,² H. G. Miller, C. B. Lipman and W. F. Gericke (175*a*) and others have confirmed and extended these observations: the last-named authors found that sulphate of ammonia was superior to nitrate of soda for barley on certain Californian soils, though it was no better than a mixture of nitrate and sulphate of soda.

Silicon does not seem to be essential in any quantity, but it occurs to so large an extent in some plants that it is not likely to be wholly useless. Wolff and Kreutzhage (315) found that soluble silicates increased the yield of oats in water cultures and also the proportion of grain, behaving, in their opinion, much like phosphates. On some of the phosphate-starved plots at Rothamsted marked crop increases are obtained by addition of sodium silicate (Table XXIV.). Hall and Morison (120*c*) conclude that silicates act by causing an

TABLE XXIV.—EFFECT OF SILICATES ON THE GROWTH OF BARLEY, 1864-1904. ROTHAMSTED.

| | Yield of Dressed Grain, bushels. | | Yield of Straw, cwt. | | Ratio Total Grain Straw | |
|---|----------------------------------|----------------|----------------------|----------------|-------------------------|----------------|
| | Without Silicate | With Silicate. | Without Silicate. | With Silicate. | Without Silicate. | With Silicate. |
| Nitrate only | 27.3 | 33.8 | 16.2 | 19.8 | 85.1 | 86.6 |
| Nitrate + phosphate | 42.2 | 43.5 | 24.6 | 25.8 | 87.2 | 85.8 |
| Nitrate + potassium salts . . | 28.6 | 36.4 | 17.9 | 21.7 | 80.6 | 85.0 |
| Nitrate + phosphate + potassium salts | 41.2 | 44.5 | 25.3 | 27.6 | 82.7 | 82.1 |

increased assimilation of phosphoric acid by the plant, the seat of action being in the plant and not in the soil. Beneficial results were likewise obtained by Jennings.³

¹ *Expt. Stat. Record*, 1900, II, 723, and 1903, 15, 565.

² Pitz, *Journ. Ag. Research*, 1916, 5, 771-780; H. G. Miller, *Journ. Ag. Research*, 1919, 17, 87-102.

³ *Soil Sci.*, 1919, 7, 201.

Boron, given as boric acid, was found by Dr. Brenchley (53*b*) to increase the growth of peas, but not of barley, in water cultures at concentrations of about 1/100,000; above this point harmful effects were produced. In Voelcker's pot experiments (290) even 1 part in 200,000 of soil proved toxic for barley, but at lower concentrations there was a slight stimulating effect. More recent experiments are recorded by Cook and Wilson.¹

Physiological Balance.

It is not only necessary to supply all the essential nutrient substances to the plant, in addition there must be maintained some kind of proportion between the various salts; this is spoken of as the physiological balance. Plant physiologists have long recognised that single salts of potassium, magnesium, sodium, etc., are toxic to plants, while a mixture of salts is not. Calcium salts are by much the most powerful reducers of this toxic effect. Thus Kearney and Cameron (145*a*) found that a root of *Lupinus albus* was just killed when immersed in '00125 N magnesium sulphate solution (7 parts per 100,000), but the effect was modified by added salts, as shown in Table XXV.

TABLE XXV.—EFFECT ON VARIOUS SALTS IN REDUCING THE TOXICITY OF $MgSO_4$. KEARNEY AND CAMERON (145*a*).

| | Alone. | + $MgCl_2$ (‘0025 N). | + Na_2CO_3 (‘0025 N). | + Na_2SO_4 (‘01 N). | + $NaCl$ (‘015 N). | + $CaCl_2$ (‘2 N). | + $CaSO_4$ (Saturated). |
|---|----------|--------------------------|----------------------------|--------------------------|-----------------------|-----------------------|----------------------------|
| Strength of $MgSO_4$ that just kills the root . . | ‘00125 N | ‘000625 N | ‘00125 N | ‘00375 N | ‘0075 N | ‘2 N | ‘6 N |

Hansteen found that the toxic effect of potassium salts used singly was overcome even when so little lime was added that the ratio $\frac{CaO}{K_2O} = \frac{1}{8.40}$. Osterhout found (220*a*) that *Vaucheria sessilis* lived for three weeks in distilled water,

¹ F. C. Cook and J. B. Wilson, *Journ. Ag. Research*, 1918, 13, 451.

but was killed in a few minutes by $\frac{3}{32}$ N NaCl, and in a few days by '0001 N NaCl; yet the toxic effect even of the stronger solution disappeared on adding one gram-molecule of CaCl_2 for every 100 gram-molecules of NaCl. It does not appear that calcium prevents the entrance of the sodium or other ion into the plant: apparently it gives greater vigour to the plant.¹ Magnesium chloride and sulphate, potassium chloride and calcium chloride were also toxic when used singly, but in admixture they formed a nutrient medium in which the plant grew normally and developed fruit even when $\frac{3}{32}$ N NaCl was also present. This action is called antagonism of ions.² Osterhout shows (220*b*) that the phenomena hold generally both for land and water plants.

Other facts are less easy to explain, such as Grafe and Portheim's observation that the toxic effects of a single salt fail to appear, or are much delayed, when sugar is supplied.³

These and many other experiments all indicate that a complex equilibrium normally exists in the cell between colloids and electrolytes which can be maintained only when the external medium has an appropriate composition.

Even when all the nutrient salts are present and the total osmotic concentration is maintained constant at a suitable level it is still possible to produce the most diverse effects on the growing plant, from violent injury to excellent growth, by varying the proportions in which the salts occur. This problem has been much investigated by Tottingham (283) and by Shive (262*a*). Tottingham studied the effects of eighty-four mixtures of KH_2PO_4 , KNO_3 , MgSO_4 and $\text{Ca}(\text{NO}_3)_2$, plus a trace of an iron salt, all of which had the same total osmotic concentration. Shive simplified the investigation by reducing the salts to three, KH_2PO_4 , $\text{Ca}(\text{NO}_3)_2$ and MgSO_4 , and using

¹ J. A. Le Clerc and J. F. Breazeale, *Journ. Ag. Research*, 1920, 18, 347; L. Maquenne and E. Demoussy, *Compt. Rend.*, 1920, 170, 420.

² For sand culture experiments see Wolkoff, *Soil Sci.*, 1918, 5, 123-150.

³ *Bied. Zentr.*, 1908, xxxvii., 571.

thirty-six different combinations of equal total concentration.

The extent of the injurious effect depends on the concentration: at 0.1 atmosphere osmotic pressure none of the solutions proved injurious to seedlings; at a higher concentration seven caused severe and four slight injury; fifteen caused various degrees of productiveness without injury.

The specific injury caused in these circumstances by monopotassic phosphate and by sulphate of ammonia to soy beans was studied by Shive (262*c*) and by Wolkoff (316) respectively.

The amount of growth produced by well-balanced solutions also depends on the total concentration, increasing up to a certain point.

The optimum ratio of nutrients for a given stage of plant development alters with the concentration; it is not the same at 0.1, 1.75, and 4 atmospheres. But it is not affected by the nature of the medium; it is the same in sand as in water culture. So also it is independent of variations in the moisture content of the sand, being the same for degrees of moistness varying from 40, 60, to 80 per cent. of the water-retaining capacity of the sand. But it is not constant for the whole range of growth of the plant, being different in seedling and ripening stages and different for the growth of "top" and of roots.

It must not be supposed, however, that the physiological balance is a rigid ratio: Hoagland and Sharp (136*c*) obtained satisfactory growth with a wide range of mixtures so long as the total supply and concentration of essential elements was adequate. Mazé has adduced evidence that physiological balance is an important factor in soils and is affected by calcium carbonate and sometimes by humus (196).

Absence of Injurious Substances.

We have seen that many salts have a toxic effect if given alone to the plant, but for our purpose we need consider only those causing injury in presence of other compounds. Two cases arise in practice: some substances are injurious even in small quantities, others only in excess.

Substances Injurious in Small Quantities: Acids and Alkalies.—H and OH ions. It has long been known that plants do not grow well on acid soils, and the conclusion has been drawn that the acidity is harmful to plants. As a general statement this is true: additions of a strong acid, such as HCl or H₂SO₄, to a culture solution or to soil soon kills the plant. But the change in reaction thus induced is vastly greater than is found in soils, and from our point of view it is necessary to know the effect of changes of the same magnitude as occur in nature. The proper basis of comparison is the hydrogen-ion concentration (see p. 113). Hoagland has shown (136*a*) that an acid condition up to 0.7×10^{-5} H ion ($P_H = 5.16$) is favourable to the growth of barley seedlings, while stronger acidity is harmful. Alkaline solutions stronger than 1.8×10^{-6} OH ion ($P_H = 8.26$) caused injury, and those stronger than 2.5×10^{-5} ($P_H = 9.40$) were extremely toxic. Salter and McIlvaine (243) obtained the best growth in slightly acid conditions: for wheat, soy beans, and lucerne $P_H = 5.94$, and for maize $P_H = 5.16$; 2.96 was harmful, and 2.16 fatal. Alkalinity was decidedly more harmful than acidity¹ (Fig. 13).

It will be shown later that the P_H value of soils varies between 3.7 and 9.7, values beyond 4.5 and 8.5 being, however, unusual. The acidity is often less than that of cell sap, the P_H value of which varies between 4.0 and 6.0.² Thus,

¹ See also J. S. Joffe, *Soil Sci.*, 1920, 10, 301.

² Truog and Meacham, *Soil Sci.*, 1918, 5, 177. For further data showing variation with stage of growth and conditions see A. R. C. Haas, *Soil Sci.*, 1920, 9, 341. For acidity of root sap (which is generally less than that of the aerial portion), H. Kappen (*Landw. Versuchs-Stat.* 1918, 91, 1-40) obtained the following P_H values:—

| | |
|-----------------------|---------|
| Wheat | 7.2 |
| Barley | 6.85 |
| Oats | 6.7-6.8 |
| Rye | 6.6 |
| Mustard | 6.2 |
| Horse beans | 6.0 |
| Lupins | 5.6-5.8 |
| Buckwheat | 5.0-5.3 |

For other determinations see C. B. Clevenger, *Soil Sci.*, 1919, 8, 217 (values 5.8-6).

direct injury to the plant caused by true acidity of the soil is probably not very frequent in nature: harmful effects of alkalinity, however, do occur.

The unsuitability of the atmosphere of industrial towns has been traced in part to the presence of acids, which affect the leaves as well as the roots. Wieler¹ found that assimilation of carbon dioxide was profoundly modified by sulphur

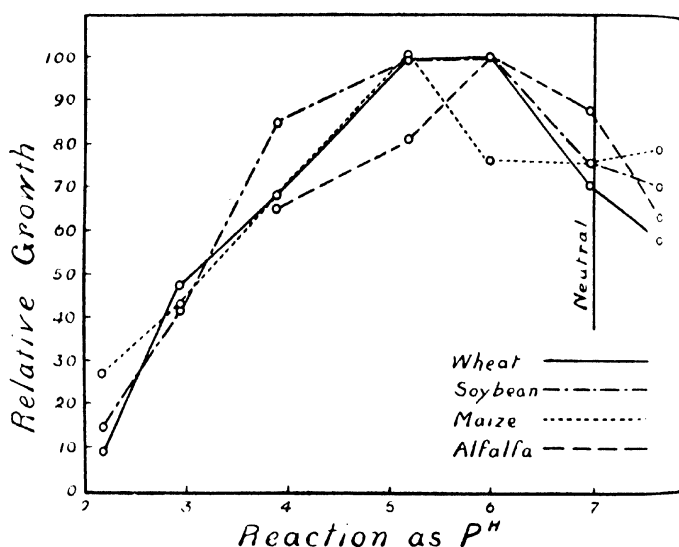


FIG. 13.—Relation between hydrogen-ion concentration (P^H value) and growth of crops. (Salter and McIlvaine, 243.)

dioxide, most injury being done in moist weather when the stomata were more widely opened and the gas could readily enter the leaf tissues. Crowther and Ruston (71) obtained the following yields from pots of Timothy, showing that acid water gradually kills the plant :—

¹ *Bied. Zentr.*, 1908, xxxvii., 572.

TABLE XXVI.—EFFECT OF ACID RAIN-WATER ON THE GROWTH OF TIMOTHY GRASS. CROWTHER AND RUSTON (71).

Weight of dry matter obtained when plants were regularly watered with :—

| | Country Rain Neutralised. | Leeds Rain (Acid). | Solution of Sulphuric Acid, Parts per 100,000 of Water. | | | | | |
|------------------|------------------------------|-----------------------|--|------|------|------|------|------|
| | | | 1 | 2 | 4 | 8 | 16 | 32 |
| 1st crop, 1908 . | 28.0 gms. | 23.8 gms. | 30.5 | 28.7 | 28.8 | 24.8 | 23.8 | 14.1 |
| 2nd crop, 1909 . | 24.9 .. | 17.5 .. | 18.2 | 17.8 | 10.0 | 8.2 | 1.8 | 0 |
| 3rd crop, 1910 . | 14.7 .. | 6.6 .. | 12.0 | 8.0 | 3.9 | 3.7 | 0 | 0 |

Metallic Salts.—Complaints are sometimes made by farmers in mining districts that their crops suffer damage from the waste products—generally metallic salts—turned into the streams from the works, especially where the water is wanted for irrigation, or where, as in Japan, rice is grown in the marshes. The damage done to pastures by the lead mines of Cardiganshire has been investigated by J. J. Griffith (115) at Aberystwyth. Clover is particularly susceptible. A heavy dressing of lime proved a useful remedy.

Zinc also causes injury in parts of Wales.¹

Traces of zinc are regarded as essential by Mazé (197). Working with larger quantities Dr. Brenchley (53*b*) was unable to find definite indications of stimulating action in water culture, although Javillier (143) claimed to obtain increases in soil. Ehrenberg (93*a*) concludes that zinc salts are always toxic when the action is simply on the plant, but they may lead to increased growth through some indirect action on the soil itself (see p. 281).

A vast number of experiments have shown that copper salts are extraordinarily toxic in water cultures or where they actually come into contact with the plant, even the minute trace sometimes present in distilled water being harmful. This property finds useful application in removing algæ from water and in killing weeds. For example, a 3 per cent. solution of copper sulphate is sprayed over cornfields in early

¹ The soil of an Anglesey garden examined at Rothamsted contained 0.78 per cent. of zinc. It proved, as might be expected, highly infertile.

spring at the rate of fifty gallons per acre to destroy charlock (*Brassica sinapis*), one of the most troublesome weeds on light soils. The solution adheres to the rough horizontal leaves of the charlock and kills the plant, but runs off the smooth vertical leaves of the wheat without doing much damage. Even the insoluble complex copper salt present in Bordeaux mixture and sprayed on to fruit trees to kill fungoid pests, was found by Amos¹ to retard assimilation of carbon dioxide by the leaf.

Copper salts do not appear to be anything like so toxic in the soil as in water culture.

It is often asserted that any toxic substance must, at proper dilutions, act as a stimulant to plants; with copper sulphate, however, Dr. Brenchley (53*a*) could obtain no evidence of increased growth in water cultures at any dilution, even down to 1 part in 10,000,000 of water, although the toxic effect was always shown. The pot experiments of Russell and Darbishire lead to the same conclusion (241*b*).

Ferrous salts are toxic and are commonly regarded as one cause of the sterility of badly aerated soils.

Aluminium salts have received attention, to them having been attributed much of the injury formerly ascribed to acidity in acid soils (see p. 112). While in low concentrations they are apparently beneficial (p. 75), at higher concentrations they are harmful, especially in acid soils.

Salts of arsenious acid were found by Dr. Brenchley to be much more toxic than those of arsenic acid; they are used as weed-killers. Greaves, however, claims to have obtained evidence that arsenic compounds stimulate the nitrogen fixing organisms in the soil;² while Green has isolated bacteria which are capable of converting arsenites into arsenates, and *vice versa*.³

Most metallic salts appear to be toxic, except those of the

¹ *Journ. Ag. Science*, 1907, ii., 257-266.

² *Journ. Ag. Research*, 1916, 6, 389-416.

³ H. H. Green, 5th and 6th Report, *Veterinary Research*, South Africa, 1915, 593-624.

few metals required for nutrition. No unexceptionable evidence of a stimulating effect on the plant has yet been obtained, although certain effects may be produced in the soil leading to increased growth (see p. 280). The literature of the subject is summarised by Dr. Brenchley in her monograph (53*d*).

Whenever infertility is traced to any of these metallic salts a good dressing of lime is usually found to be an effective antidote.

Various Other Substances.—Sulphuretted hydrogen is extremely toxic, so also is ammonium sulpho-cyanide which, in the early days, used to cause trouble as an impurity in ammonium sulphate made from gas liquor. It is rarely, if ever, found now. Toxic nitrogen compounds include nitrites, which have to be removed from synthetical calcium nitrate used for manure, the dicyano-diamide associated with commercial cyanamide, and ammonium salts at too high a concentration. None of these, however, are for long harmful in the soil, since all are ultimately converted into nitrates. Perchlorates are harmful and used sometimes to occur in sodium nitrate, but they are now carefully removed.

Substances Injurious in Large Quantities: Carbon Dioxide.—In an interesting series of investigations Kidd (147) has shown that CO_2 exerts a marked inhibiting effect on the germination of seeds, even though all other conditions are favourable. The seed is not permanently affected, and it will germinate freely, though not always immediately, when the CO_2 is removed. He suggests that this is the cause of the remarkable dormancy of certain seeds, especially weed seeds, buried below a certain depth in the soil; some of these will survive for years, and will produce a copious and vigorous crop of weeds when brought to the surface by deeper ploughing or breaking up of grass land.¹

Soluble Salts.—In many arid districts the soil contains such large quantities of sodium and potassium salts that the soil water is too concentrated to permit of plant growth. Sodium carbonate not infrequently occurs and directly poisons

¹ W. E. Brenchley, *Journ. Ag. Science*, 1918, 9, 1-31.

the plant. Such soils are called alkali soils: they may be treated with gypsum, or, still better, carefully washed with irrigation water, adequate provision being simultaneously made for drainage.

Calcium Carbonate is sometimes considered harmful because plants are liable to chlorosis on chalky soils. It is equally probable, however, that the general soil conditions are responsible for the disease (see p. 304).

Magnesium Salts.—The toxicity of magnesium salts was discovered by Tennant in the eighteenth century in studying the alleged harmful effects of certain limestones found near Doncaster (280). Modern investigations¹ on magnesian limestone, however, have failed to show any harmful effect; indeed, in the Woburn experiments (290) Voelcker has obtained an actual benefit both on wheat and on mangolds by using magnesia (MgO). But the soluble salts, the sulphate and especially the chloride, are harmful. Cases are reported by Loew where excess of magnesia in the soil has caused infertility; none, however, have fallen under the writer's observation in this country. The soil of the Greenville Experimental Farm, Utah, is rich in magnesia—containing over 6 per cent. of MgO—and is remarkably fertile. It also contains, however, 17 per cent. of CaO and 20 per cent. CO₂.² As already stated, any injurious effect can be overcome by treatment with lime.

Effects of Salts on Germination.—Salts generally cause a retardation in the rate of germination; some of Guthrie and Helms' (117) results are given in Table XXVII. Sigmund has studied the effects of a very large number of substances (267). The technical interest in the work lies in the fact that seeds are sometimes treated with antiseptics before sowing in order to kill any spores of disease organisms, and, moreover, certain soluble salts—artificial manures—are often put into the soil about the same time as the seeds are sown.

¹ See, e.g., *New Jersey Bull.*, 267, 1914, and on the other side *Durham Coll. Bull.*, 12, 1915.

² J. E. Greaves, R. Stewart, and C. T. Hirst, *Journ. Ag. Research*, 1917, 9, 301.

TABLE XXVII.—EFFECT OF SOLUBLE SALTS ON GERMINATION. GUTHRIE AND HELMS (117).

| | Sodium Chloride, per cent. | | Sodium Carbonate, per cent. | | Sodium Chlorate, per cent. | | Arsenic Trioxide, per cent. | |
|------------------------|-------------------------------|------|--------------------------------|------|-------------------------------|-------|--------------------------------|------|
| | Barley. | Rye. | Barley. | Rye. | Barley. | Rye. | Barley. | Rye. |
| Germination affected . | 0·10 | 0·10 | 0·25 | 0·25 | 0·005 | 0·004 | 0·6 | 0·20 |
| „ prevented . | 0·25 | 0·40 | 0·60 | 0·50 | 0·007 | 0·006 | — | 0·4 |
| Growth affected . | 0·10 | 0·15 | 0·15 | 0·25 | 0·003 | 0·002 | 0·05 | 0·15 |
| „ prevented . | 0·20 | 0·20 | 0·40 | 0·40 | 0·006 | 0·004 | 0·10 | 0·30 |

When a solution comes in contact with a seed it does not necessarily enter as a whole. Adrian Brown (58) has shown that the barley seed is surrounded by a membrane which has the remarkable property of keeping out many dissolved substances and allowing the water only to pass in, so that the solution loses water and becomes more concentrated. A number of substances can, however, pass through the membrane, and to these H. E. and E. F. Armstrong (5) have applied the term Hormones. In general they have no great affinity for water; in the Armstrongs' nomenclature they are *anhydrophilic*: they pass into the cell and there disturb the normal course of events. Ammonia, toluene, ether, chloroform, are all highly effective hormones readily entering the cells of seeds, leaves, etc., and hastening the normal sequence of processes.

Supposed Stimulation of Plants by Electricity, Heat, and Radium.

The Electric Discharge.—It has often been stated that an electric discharge increases the rate of growth of plants either by direct action on the plant, or by indirect action in the soil. As far back as 1783 the Abbé Bertholon (34) constructed his *electro-végétomètre*, a kind of lightning conductor that collected atmospheric electricity and then discharged it from a series of points over the plant. The view that atmospheric electricity is an important factor in crop growth has always found

supporters in France. Grandeau (112*b*) stated that plants protected from atmospheric electricity by a wire cage made less growth than control plants outside. Lesage¹ confirmed this observation, but found that silk thread caused as much retardation as wire, so that the effect is not necessarily electrical: in point of fact the rate of evaporation was considerably less under the cage than in the open.

Instead of relying on atmospheric electricity Lemstrom (171) generated electricity on a large scale and discharged it from a series of points fixed on wires over the plant. This method has been used at Bitton, near Bristol, and studied on the electrical side by Sir Oliver Lodge, on the botanical side by J. H. Priestley (231), and on the practical side by J. E. Newman, J. H. Priestley, I. Jørgensen, and Miss Dudgeon. Numerous field experiments are recorded, but there is usually some uncertainty about the check plots. The Bromberg experiments (104*a*) gave negative results. Further studies are in hand by V. H. Blackman who has put the whole subject on a sound basis for investigation.

Various Rays.—Experiments by Miss Dudgeon suggest that the rays of the Cooper-Hewitt mercury vapour lamp² may have a stimulating effect, accelerating germination and increasing growth. Priestley found that the rays from a quartz mercury vapour lamp were harmful at close range, whilst farther off they stimulated growth. There is much scope for work in this direction; the problem is of great economic importance, because of the enhanced market value of early crops.

Effect of Heat.—Molisch³ has shown that perennial plants steeped in hot water towards the close of their deepest period of rest come at once into activity. His hypothesis is that the "rest" required by plants is of two kinds, the *freiwillig* rest due to external conditions and therefore capable of being shortened, and the *unfreiwillig* rest inherent in

¹ *Compt. Rend.*, 1913, 157, 784.

² A glass envelope was used.

³ *Das Warmbad als Mittel zum Treiben der Pflanzen*, 1909, Prague.

the nature of the plant. Parkinson¹ has tested the method with satisfactory results; spirea, rhubarb, seakale, etc., steeped for twelve hours in water at 95°, at the end of November, or early in December, made rapid growth when subsequently forced.

Effect of Radium.—R. J. Strutt has shown² that the typical soil deposits contain measurable amounts of radioactive substance equivalent to 0.25 (but more usually 1) to 5.8×10^{-12} grms. of radium per gram. Zircon and apatite are much richer, the figures being 75 to 865×10^{-12} and 11 to 30×10^{-12} respectively. Joly³ finds that the amount of radium emanation in soil air is many thousand times greater than in the atmosphere; J. Satterly⁴ at Cambridge gives a lower estimate, *viz.* 2×10^{-12} curie per litre, or 2000 times the usual amount in the atmosphere; while J. C. Sanderson⁵ in America estimates the amount in 1 c.c. of soil air as the quantity in equilibrium with 2.4×10^{-13} grms. of radium. Among the many remarkable properties of radium it was perhaps natural to expect that it might have some definite effect on plants or micro-organisms. The suggestion has even been made that radium emanations might, under suitable conditions, cause sufficient increase in the amount of growth to justify its use in horticulture and agriculture. The early observations of Dixon and Wigham⁶ at Dublin, however, did not seem very promising; 100 seeds of cress (*Lepidium sativum*) were uniformly distributed on an even surface of moist quartz sand, and after germination had taken place, a sealed tube containing 5 mgms. of radium bromide was set 1 cm. above the central seed. The seedlings grew up, but without any curvature indicating positive or negative "radio-tropism," and the only noticeable effect was a slight depression

¹ *Journ. South-Eastern Agric. Coll.*, 1909, **19**, 245-257.

² *Proc. Roy. Soc.*, 1906, **77a**, 472, and 1907, **78a**, 150.

³ *Sci. Proc. Roy. Soc.*, Dublin, 1911, **13**, 148.

⁴ *Proc. Camb. Phil. Soc.*, 1912, **16**, 514. The soil air was taken at a depth of 100-150 cms. For his estimates of the amount in the atmosphere see *Phil. Mag.*, 1910 (vi.), **20**, 1.

⁵ *Amer. J. Sci.*, 1911 (iv.), **32**, 169.

⁶ *Proc. Roy. Soc.*, Dublin, 1904, **10**, 178-192.

of growth in those within 1 cm. radius of the tube. As stronger preparations of radium became available more definite retardations and inhibitions were observed; thus Gager, in an elaborate report,¹ noted a more or less complete inhibition in cell activities in younger and especially embryonic tissues, with a few exceptions. The action of radium through the soil, however, was different; germination and growth were both accelerated, and the plants farthest away were stimulated most. Acqua² found that different plants, and even different organs of the same plant, were differently affected, the root system in general responding more markedly than the aerial parts, and in his experiments being arrested in their development. The intensity of the radiation, however, is important, and G. Fabre,³ using *Linum catharticum* as a test plant, was able to obtain increased development and germination of seedlings by working with emanations up to 1.5 microcuries per 2 litres of air, and to retard development by using emanations of 40 microcuries per litre of air. H. Molisch⁴ obtained a like result; young plants of vetches, beans, sunflower, etc., were stimulated in growth by weak emanations, but checked, or entirely stopped, by stronger ones. He further claimed that the "rest period" could be broken by the radium emanation, and he forced lilac into bloom in November by attaching pipettes containing small quantities of radium chloride to the terminal buds.⁵ In his earlier experiments he, like Dixon and Wigham, failed to detect any radiotropism, but later on he found indications in the case of certain heliotropically-sensitive plants, e.g. oats and vetches.⁶

These, and similar, results, naturally suggested that the residues left after the extraction of radium, but still containing radio-active material, might have definite manurial value, and it was not long before definite statements were forthcoming. Baker⁷ claimed that increased yields of wheat and radishes

¹ *Mem. New York Bot. Gard.*, 1908.

² *Ann. Bot.* (Rome), 1910, **8**, 223-238.

³ *Compt. Rend. Soc. Biol.* (Paris), 1911, **70**, 187-188.

⁴ *Umschau*, 1913, **17**, 95-98.

⁵ *Oesterr. Gart. Ztg.*, 1912, **7**, 197-202.

⁶ *Sitzber. K. Akad. Wiss.* (Vienna), 1911, **120**, 305-318.

⁷ *Journ. Roy. Soc. Arts*, 1913, **62**, 70-78.

had been obtained by mixing 1 part of radio-active material (2 mgs. Ra per ton) with 10 of soil. It is true that Stoklasa's¹ results were negative (although in his other experiments radium emanations increased growth to a marked extent), but this did not prevent the introduction of radio-active fertilisers, and the enterprising syndicates and companies concerned were by no means loth to push their wares. These were investigated by Martin H. F. Sutton,² the experiments being made with radishes, tomatoes, potatoes, onions, carrots, and marrows, some grown in pots, others in plots out of doors. Eight different radium residues were used, in addition to pure radium bromide; the dressings were so arranged that equivalent quantities of radium were given in each case ($\frac{1}{100}$ grm. radium bromide to 15 lb. of soil : $2\frac{1}{2}$ times this amount per sq. yard to the plots).

In no case was there any clear evidence of increased growth, even the pure radium bromide seemed to be without action.

We are therefore left with the apparent discrepancy already observed on p. 35. The work of the physiologists, assuming it to be sound, indicates that radium emanation is capable of stimulating certain cell activities. Sutton's results show that such stimulus, if it exists, does not affect the final growth of the plant. This discrepancy is periodically confronting the agricultural investigator. Thus, Dr. Winifred Brenchley at Rothamsted has failed to obtain increases in growth by supplying plants with inorganic poisons which have been supposed to stimulate certain cell functions in suitable dilutions. The result opens up the prospect of an interesting discussion, but it also shows the danger of arguing from a simple physiological observation to a complex phenomenon like the growth of a plant in soil.

Zwaardemaker³ has obtained some interesting results in the case of animal organs which deserve close study by plant physiologists.

¹ *Chem. Ztg.*, 1914, **38**, 841-844.

² Messrs. Sutton's Bull., No. 6, 1916.

³ *Journ. Physiology*, 1920, **53**, 273, discussed by V. H. Blackman in *Annals of Botany*, 1920, **34**, 299.

CHAPTER III.

THE COMPOSITION OF THE SOIL.

It is well known that only the top six or eight inches of the soil is suited to plant life, and that the lower part, or subsoil, plays only an indirect part in plant nutrition. We shall, therefore, confine our attention almost exclusively to the surface layer.

The soil was in the first instance derived from rocks, partly by disintegration and partly by decomposition. In most cases the fragments split off were sooner or later carried away by water and deposited at the bottom of a river or sea. There they mingled with residues of living organisms which have subsequently played an important part in the history of the soil as its chief source of calcium carbonate and calcium phosphate. In course of time the material accumulated to considerable depths; then, as the result of some earth change, the water retreated leaving the deposited material as dry land or rock. No sooner was this exposed to the air than it began once again to undergo disintegration and erosion. Air, water, and frost all played a part in the disintegration process; water and sometimes ice have acted as transporting agents. For immense ages the particles have been subjected to these actions, and the fact that they have survived shows them to be very resistant and practically unalterable during any period of time that interests us. Reference to Table LXXXVII., p. 332, shows that the particles in the surface soil which have been exposed to weathering ever since the soil was laid down, and in some cases, to cultivation for some hundreds of years, are almost indistinguishable in size from those in the subsoil which have been protected from all these changes.

However, the soil particles are not wholly unalterable. The rain water and its dissolved carbonic acid exert a slight solvent action, and the soil water always contains small amounts of calcium and magnesium compounds, silica, and other substances in solution. Each individual particle only loses a very minute amount of substance to the soil water, and its life is extraordinarily long; nevertheless dissolution is perpetually taking place. The surface soil contains less of the smallest, and, therefore, most easily attacked, particles than the subsoil.

In any region where the rainfall and temperature conditions are favourable, soil rapidly covers itself with vegetation; even a bare rock surface is not without its flora. The first vegetation must obviously have obtained its mineral food from the dissolved material of the soil particles, but when it died and decayed all the substances taken up were returned to the soil, so that subsequent vegetation has food from two sources: from the substances dissolved direct out of the soil particles during the life of the plant, and from those dissolved out at earlier times and taken up by previous races of plants. Thus in the natural state, and where the vegetation is not removed, the mineral plant food can be used over and over again and indeed tends to accumulate as fast as it is extracted from the soil particles by the rain water.

The plant, however, returns to the soil more than it takes away; during its life it has been synthesising starch, cellulose, protein, and other complex unstable and endothermic material, much of which falls back on the soil when it is dead. This added organic matter introduces a fundamental change because it contains stored-up energy; the difference between the soil as it now stands and the original heap of mineral matter is that the soil contains sources of energy while the mineral matter does not. Hence it soon becomes the abode of a varied set of organisms, drawing their sustenance and their energy from the accumulated residues, and bringing about certain changes to be studied later; some, as we shall see, are capable of fixing gaseous nitrogen and so increasing the supply

of protein-like compounds, whilst others can assimilate carbon dioxide.

Thus the complex that we speak of as the soil consists of four parts :—

1. The mineral matter derived from rock material, which constitutes the frame-work of the soil and is in the main unalterable, but it contains some reactive decomposition products.
2. The calcium carbonate and phosphate (the latter being usually in much smaller amount), and organic matter derived from marine or other organisms deposited simultaneously with the soil.
3. The soil water, a dilute solution of carbonic acid containing small quantities of any soluble soil constituent.
4. The residues of plants that have grown since the soil occupied its present position, consisting of the mineral plant food taken up from the soil water and of part of the complex organic matter synthesised during their life period. As the source of energy for the soil population this may be regarded as the distinguishing characteristic of soils.

These four constituents are invariably present, but not in the same proportion; their relative abundance affords the basis on which soils are classified. From the agricultural point of view we thus have : (*a*) mineral soils consisting mainly of rock material, subdivided into sands, loams, and clays; (*b*) calcareous soils containing notable amounts of chalk or limestone; (*c*) alkali soils rich in soluble, saline matter; (*d*) acid humus or peat soils where much organic matter has accumulated in absence of calcium carbonate; (*e*) neutral humus soils where much organic matter has also accumulated, but in presence of sufficient calcium carbonate to prevent acidity.

By far the greater proportion of agricultural soils belong to the first group.

The Mineral Portion of the Soil.

It is usual to divide the soil into a number of fractions by a sedimentation process, and this method has been used for a

large number of analyses, which have given information of considerable value to the student and the cultivator. The method is fundamentally defective in that the grouping is quite arbitrary, sharp lines being drawn where none exist in Nature, and the soil is represented as a mixture of five or six different substances when in point of fact the number of components is indefinitely large. It is very difficult to use the resulting figures for further investigations: they cannot be plotted on curves or reduced to simple factors. They can, it is true, be set out in columns which are very convenient for lecture purposes. Some limited success has followed the attempts to correlate the figures with other soil properties, as will be shown later; but in the main the actual figures obtained have not proved very fruitful to investigators, though the broad general results have been useful.

Very much better results might be expected if a distribution curve could be obtained, showing how the particles are distributed according to size.

A certain amount of artificiality seems inevitable, and one must still keep to the conventional "effective radii" and deal with the soil particles, not as they are, but as they would be if they were perfect spheres. A distribution curve on these lines, while not perfectly expressing the soil conditions, would be a great advance on anything that we have at present.

A serious effort to obtain such a curve has been made by Sven Odén, whose elegant method of mechanical analysis deserves serious attention from soil investigators. Instead of ascertaining the weights of the fractions of soil falling between certain limits of size, Odén proceeds in the reverse order, and ascertains the time taken for small successive equal weights to fall through a column of water. A suspension of soil in water is poured into a cylinder near the bottom of which is a large flat plate attached to one arm of a balance, the other arm being counterpoised and containing in its pan a small weight. As soon as the weight of the soil particles settling on the plate begins to exceed the weight in the pan the balance moves: this makes an electric connection which registers the time on

a chronograph and causes a second weight to fall into the pan, thereby restoring the balance to its original position (Fig. 14). The process is repeated when the weight of sediment again just exceeds the weight on the pan.

The second step consists in calculating from the known

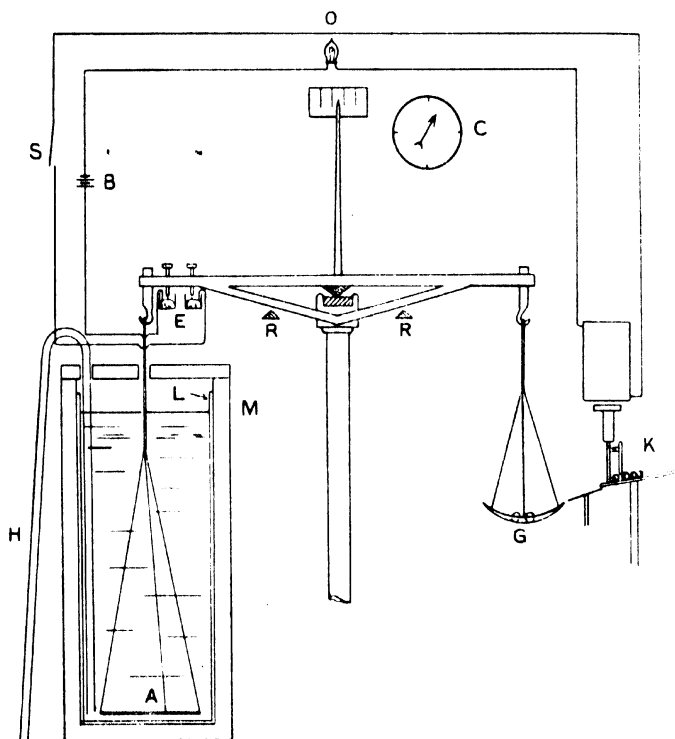


FIG. 14.—Sven Odén's apparatus for mechanical analysis of soil diagrammatically represented (218c).

laws of motion of solids in fluids the mass or number of particles of any given radius present in the soil : but as the actual particles are very irregular in shape it is necessary to adopt an "equivalent" or "effective" radius, i.e. the radius of a sphere which would fall with the same velocity as the particle.

Odén gives a formula for effecting the calculation, but its use requires some mathematical training.¹

The type of curve finally obtained is shown in Fig. 15. This is a *mass distribution* curve: not a frequency curve. On the horizontal axis are plotted successive values of the radii. The axis of y represents a complex function which gives the percentage weight of particles comprised between successive integral values of μ . Thus the percentage weight of particles between 1μ and 2μ in diameter is the area bounded by ordinates drawn at points 1 and 2 on the axis of x : without

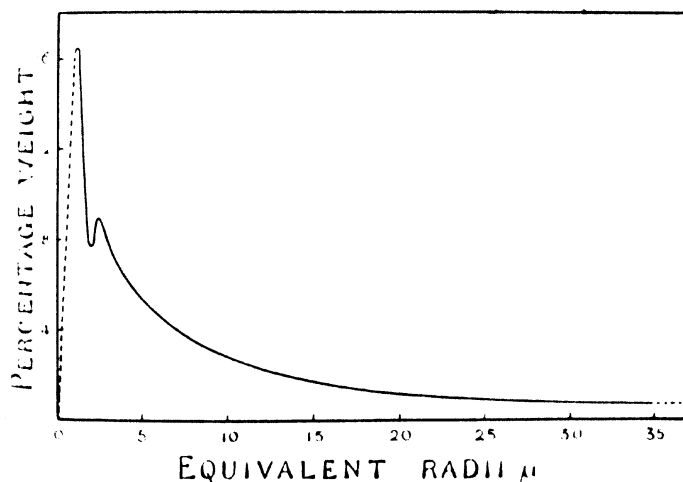


FIG. 15.—Mass distribution curve obtained by Odén's method of soil analysis. sensible error it is represented by the ordinate drawn from the point 1.5.

It is improbable that this could ever become a working analytical method; but as a method for investigation it surpasses any other at present available, because for the first time it affords the possibility of representing the soil fractions by a distribution curve of the type familiar to physicists and mathematicians.

¹ A full description of the method and the mode of calculating the results will be given in B. A. Keen's monograph in this series. A simpler method is described by O. Wiegner, *Landw. Versuchs-Stat.*, 1918, 91, 41-80.

TABLE XXVIII.—NAMES AND SIZES OF FRACTIONS OBTAINED BY MECHANICAL ANALYSIS OF SOILS IN DIFFERENT COUNTRIES.

| British. | | American (Bureau of Soils). | | German older work ¹ (Verband landw. Versuchs-Stat.). | | Atterberg ² (Suggested for International Use and adopted in Germany). ³ | |
|----------------------|---|--------------------------------|---|--|---|---|---|
| Name of Fraction. | Limits of Diameter of Particles, mm. | Name of Fraction. | Limits of Diameter of Particles, mm. | Name of Fraction. | Limits of Diameter of Particles, mm. | Name of Fraction. | Limits of Diameter of Particles, mm. |
| Fine gravel | 3-1 | Fine gravel | 2-1 | Steine | above 5 | Kies | above 2 |
| Coarse sand | 1-0.2 | Coarse sand | 1-0.5 | Sehr grober sand | 5-2 | | |
| | | Medium sand | 0.5-0.25 | Grober sand | 2-1 | Sand | 2.0-0.2 |
| Fine sand | 0.2-0.04 | Fine sand | 0.25-0.10 | Mittel körniger sand | 1-0.5 | | |
| | | Very fine sand | 0.10-0.05 | Feiner sand | 0.5-0.2 | Mo or Fein sand | 0.2-0.02 0.2-0.06 |
| Silt | 0.04-0.01 | Silt | 0.05-0.005 | Sehr feiner sand | below 0.2 | Mehl sand | 0.06-0.02 |
| Fine silt | 0.01-0.002 | | | Mineral staub | | Schluff (or Staub) or grober Schluff | 0.02-0.002 0.02-0.006 |
| Clay | below 0.002 | Clay | below 0.005 | Ton | | feiner Schluff | 0.006-0.002 |
| | | | | | | Schlamm (or Ton) | below 0.002 |

¹ *Landw. Versuchs-Stat.*, 1802, 42, 154, and 1803, 43, 335. The first five fractions are separated by sieves, and the others in Kühn's sedimenting cylinder. ² Ramann adopts the American limits but divides the clay into *Feiner Staub* '005-'0015 mm., and *Schlamm*, below '0015 mm.

³ *Internat. Mitt. f. Bodk. Landw.*, 1912, 2, 312-313.

⁴ *Ibid.*, 1911, 4, 31

For practical purposes it is necessary to have resort to simpler but less exact methods.

By the method of mechanical analysis described in the appendix the particles of soil can be sorted out into fractions, each falling within certain specified limits of diameter; but unfortunately there is no international agreement as to the limits, so that the same words are used in different countries with different meanings. Some of the commoner units are given in Table XXVIII.

The justification of the .002 mm. limit for clay adopted in Britain is that a tolerably sharp change in the physical properties of bodies does occur at or about this point.¹

The difference between the British and the American units can be considerably reduced by splitting the fine silt fraction into two, *viz.* 0.01 to 0.005 mm. diameter, and 0.005 to 0.002 mm. diameter. This does not greatly lengthen the analysis, and it should always be done² when there is any likelihood of comparison with American results. There still remain small differences in the fine sand and silt which in many cases would not greatly affect the discussion.

If none but pulverising forces had been at work during soil formation the soil particles would be identical in composition with the original rock. But weathering and leaching have always wrought changes, and in extreme cases only the most resistant minerals have survived unaltered. A succession of grades may therefore be expected, shading off imperceptibly one into the other: from the extreme grade where the changes have been at a minimum and the soil particles, both coarse and fine, are complex in composition: through the intermediate grades where more change has occurred, but a number of minerals can still be found in the coarse particles: to the other extreme where the coarse particles consist almost wholly of silica, everything else having gone. The case of minimum change is exemplified in arid soils. The intermediate case is seen in soils derived direct from igneous or old rocks and

¹ R. Zsigmondy, *Colloidal Chemistry*, *trs.* E. B. Blair, 1917.

² See p. 355 for method.

either left *in situ* or transported only a short distance, such as the soils investigated mineralogically by Lagatu (82) in France, those studied chemically by Hendrick and Ogg (132) in Scotland, and by Robinson (240) in N. Wales, and various glacial and loessial soils of the United States. The case of extreme change is shown in the secondary and tertiary soils of the south-eastern part of England and in the soils of the Atlantic coastal plains of the United States.

These grades are illustrated by the following summary by McCaughey and William (186) of the minerals present in the sand and silt fractions separated from various United States soils :—

| | | No. of Soils. | Sand Fractions. | | Silt Fractions. | |
|--------|----------------------|---------------|-----------------------------|---------|-----------------------------|---------|
| | | | Minerals other than Quartz. | Quartz. | Minerals other than Quartz. | Quartz. |
| Case 1 | Arid | 3 | 37 | 62 | 42 | 58 |
| Case 2 | Residual | 12 | 15 | 85 | 21 | 79 |
| | Glacial and Loessial | 6 | 12 | 88 | 15 | 85 |
| Case 3 | Marine | 4 | 5 | 95 | 8 | 92 |

The clay fraction cannot be dealt with by mineralogical methods: this indeed is their weakness, they break down for the finest particles where they would be most helpful.¹

Failyer, Smith, and Wade (97) have made numerous chemical analyses which also show the successive eliminations of minerals other than quartz in these grades of soil :—

¹ An improvement in technique has been effected by Victor M. Moscati (*Les dépôts Nilotiques des Gazayer et Saouahel d'Égypte. Bull. de l'Inst. d'Égypte*, 1919, I, 151-180).

| | Percentage of K ₂ O in | | | Percentage of CaO in | | | Percentage of P ₂ O ₅ in | | |
|------------------|-----------------------------------|-------|-------|----------------------|-------|-------|--|-------|-------|
| | Sand. | Silt. | Clay. | Sand. | Silt. | Clay. | Sand. | Silt. | Clay. |
| Type 1 Arid . . | 3.05 | 4.15 | 5.06 | 4.03 | 9.22 | 8.03 | .19 | .24 | .45 |
| Type 2 Glacial . | 1.72 | 2.30 | 3.07 | 1.28 | 1.30 | 2.69 | .15 | .23 | .86 |
| Residual . | 1.60 | 2.37 | 2.86 | .50 | .82 | .94 | .07 | .22 | .70 |
| Type 3 Coastal . | .37 | 1.33 | 1.62 | .07 | .19 | .55 | .03 | .10 | .34 |

Table XXIX. shows the difference in composition between the fractions obtained by Hendrick and Ogg from the Aberdeen soil, belonging to the intermediate grade, and the more completely washed and weathered soils studied by Hall and Russell, where practically nothing but quartz had survived in the coarse particles.

So far as is known all the coarser particles are chemically inert. The clay fraction, on the other hand, stands out in sharp contrast both in composition and in chemical and physical properties.¹ At least two groups of clay were recognised by Hall and Russell, one associated with fertile soils, the other with less fertile soils. The high proportion of iron and alumina in the latter case is not causally connected with infertility as the clay from fertile soils in North Wales contained even more (Robinson (240)). The analytical figures throw very little light on the constitution of the clay beyond showing that it is not a simple silicate expressible by a definite chemical formula.

By successive extraction with acids of increasing concentration van Bemmelen found (22) two distinct groups of silicates in the Dutch alluvial soils, one soluble in dilute hydrochloric acid in which the ratio $\frac{\text{molecules of SiO}_2}{\text{molecules of Al}_2\text{O}_3}$ = 3 to 5,² the other soluble only in hot, strong sulphuric acid in which the ratio is

¹ For some comparable German analyses of clay see E. Blanck, *Landw. Versuchs-Stat.*, 1918, 91, 85-92.

² The higher numbers were obtained from sandy clays and the lower from heavy clays. As the silica was insoluble in the acid it was extracted by digesting the residue for a few minutes at 55° with dilute alkali of sp. gr. 1.04.

TABLE XXIX.—SHOWING COMPOSITION OF THE FRACTIONS OBTAINED FROM MUCH WASHED AND WEATHERED SOIL (S.E. ENGLAND WHERE PRACTICALLY NOTHING BUT QUARTZ SURVIVES IN THE COARSE PARTICLES, IN COMPARISON WITH THE LESS DECOMPOSED SOIL FROM ABERDEEN, WHERE MORE OF THE ROCK MINERAL (GRANITE) SURVIVES. (HALL AND RUSSELL (121) FOR S.E. ENGLAND, AND HENDRICK AND OGG (132) FOR ABERDEEN.) FOR SOILS OF N. WALES *see* ROBINSON (240).

CHEMICAL ANALYSIS OF MECHANICAL FRACTIONS, CALCULATED AS PERCENTAGES OF DRY MINERAL MATTER.

| | SiO ₂ | | Al ₂ O ₃ | | Fe ₂ O ₃ | | CaO | | MgO | | K ₂ O | | P ₂ O ₅ | |
|-------------|------------------|-----------|--------------------------------|-----------|--------------------------------|-----------|------------------|-----------|------------------|-----------|------------------|-----------|-------------------------------|-----------|
| | S.E. of England. | Aberdeen. | S.E. of England. | Aberdeen. | S.E. of England. | Aberdeen. | S.E. of England. | Aberdeen. | S.E. of England. | Aberdeen. | S.E. of England. | Aberdeen. | S.E. of England. | Aberdeen. |
| Fine gravel | 94.4 | 85.0 | 3.0 | 8.6 | 2.1 | 1.1 | 0.4 | 0.9 | 0.8 | 0.4 | 0.6 | 1.5 | 0.06 | 0.07 |
| Coarse sand | 93.9 | 83.9 | 1.6 | 9.3 | 1.2 | 1.1 | 0.4 | 1.8 | 0.5 | 0.4 | 0.8 | 1.8 | 0.05 | 0.08 |
| Fine sand | 94.0 | 73.9 | 2.0 | 13.5 | 1.2 | 4.2 | 0.4 | 3.0 | 0.04 | 1.0 | 1.5 | 1.7 | 0.02 | 0.1 |
| Silt | 89.4 | 70.1 | 5.1 | 14.0 | 1.5 | 5.8 | 0.8 | 2.1 | 0.3 | 1.1 | 2.3 | 1.5 | 0.03 | 0.2 |
| Fine silt | 184.1 | 67.2 | 7.2 | 18.9 | 2.6 | 7.8 | 1.1 | 1.4 | 0.2 | 1.6 | 3.2 | 2.5 | 0.1 | 0.3 |
| | 264.3 | | 19.3 | | 7.6 | | 2.2 | | 0.4 | | 5. | | 0.4 | |
| Clay | 53.2 | 44.1 | 21.2 | 27.6 | 13.2 | 21.8 | 1.6 | 0.6 | 1.0 | 1.6 | 4.9 | 1.1 | 0.4 | 0.4 |
| | 49.0 | | 29.8 | | 13.1 | | 1.5 | | 1.0 | | 3.4 | | 0.7 | |

¹ Fraction .01 to .005 mm.

² Fraction .005 to .002 mm.

These two fractions together constitute fine silt.

⁴ From less fertile soils.

approximately equal to 2. Other soils of volcanic origin from Java gave up larger amounts of base relative to the silica, but in no case were the ratios constant whole numbers; the alkaline bases showed the same lack of constancy in the ratios to Al_2O_3 .

TABLE XXX.—RATIO MOLECULES OF SiO_2 EXTRACTED FROM VARIOUS
MOLECULES OF Al_2O_3
SOILS. VAN BEMMELIEN (22).

| Solvent. | Temperature and Time of Extraction. | Alluvial Soils, Holland. | | Volcanic Soils, Java. | | Laterite Soils, Surinam. |
|---------------------------------|-------------------------------------|--------------------------|-----|-----------------------|-----|--------------------------|
| HCl of sp. gr. 1.03 | 15 mins. at 55° | 3.7 | 5.0 | .9 | 2.1 | 1.1 |
| HCl of sp. gr. 1.2 | 1 hour boiling temp. | 3.4 | 4.6 | 2.2 | 2.7 | 1.6 |
| H_2SO_4 conc. . | — | 2.0 | 2.4 | 3.2 | 2.0 | 1.6 |

Alkaline bases extracted from a heavy clay, Surinam.

| Solvent. | Temperature of Extraction. | Al_2O_3 Dissolved, per cent. | Ratio Mols. SiO_2 Mols. Al_2O_3 | Mols. of Bases Extracted for 1 Mol. of Al_2O_3 . | | | |
|-------------------------------|----------------------------|--|--|--|------|-------------------|--------------------|
| | | | | CaO. | MgO. | K ₂ O. | Na ₂ O. |
| HCl of sp. gr. 1.03 | 55° | 1.2 | 1.3 | .33 | .83 | .10 | .01 |
| HCl of sp. gr. 1.1 | 100° | 3.4 | 2.7 | .05 | .32 | .08 | |
| HCl of sp. gr. 1.2. | boiling | 4.6 | 2.7 | .03 | .14 | .09 | |
| HCl of sp. gr. 1.2. | " | 2.5 | 2.7 | .03 | .10 | .10 | |
| HCl of sp. gr. 1.2. | " | 1.9 | 2.7 | .03 | .08 | .12 | |
| Conc. H_2SO_4 | — | 8.8 | 2.0 | .005 | .06 | .17 | .02 |

Different soils gave up different proportions of alkaline bases, but again without showing definite simple ratios one to another. Detailed studies of clay revealed the presence of chemically unchanged crystals of the original silicates and also of easily soluble substances including a fusible group with ratio molecules of SiO_2 varying from 3 to 6, and a silicate molecules of Al_2O_3 resembling kaolin with ratios varying between 2 and 3. The easily soluble material represents the products of weathering since it does not occur in rocks. If it were a definite chemical compound the ratio of its constituents should be constant whole numbers, but this is not the case. It behaves, however,

precisely like a solid solution and is therefore regarded by van Bemmelen as an "absorption compound," SiO_2 , $m\text{Al}_2\text{O}_3$, $n\text{Fe}_2\text{O}_3$. . . $p\text{H}_2\text{O}$, in which the constituents are not chemically united but are held by the feeble forces manifested by colloids in their attractions one for the other.¹

The Physical Properties of the Various Fractions.—

Serious studies of the soil by competent physicists have scarcely been attempted as yet, and the work hitherto done can only be regarded as preliminary. The fundamental difficulty in applying the ordinary physical methods is to synthesise the soil; numerous studies have been made of the physical properties of sand, silt, clay, etc., considered as separate entities, but no one has worked out the resultant when all the varying grades of sand, silt, and clay are intimately mingled, or drawn up a scheme or formula to express the properties of the soil in terms of the mechanical analysis. More useful results are obtained by the method of correlation; soils of known properties are analysed and the results are correlated so far as is possible with the properties; even this method, however, can only be used very crudely, because the physical properties of the soil as a whole cannot at present be expressed by definite numbers. Only a very general summary will therefore be attempted.

The Clay Fraction.—The word "clay" is unfortunately used in many senses; the soil worker and the ceramic chemist in particular attach widely different meanings to it. In soil investigations clay is the material of less than .002 (or in the U.S.A. .005) mm. diameter: in ceramic work it is the material of 0.1 mm. diameter downwards. Clay in the soil sense may be regarded as a plastic colloid, but its special properties are seen only when a certain amount of water is present.² If it is well rubbed with water it becomes very sticky and absolutely impervious to air or water; it is also

¹ For Gedroiz' method of estimating the zeolitic silicic acids see *Bull. Internat. Instit.* (Rome), 1917, 8, 1190.

² Older work on the constitution of clay is summarised by Rohland in Abegg's *Handbuch der Anorganischen Chemie*, 1906, 3, 97-119.

highly plastic, and can be moulded into shapes which remain permanent on drying and baking. It shrinks very much on drying and absorbs heat; on moistening again, however, there is a considerable swelling and evolution of heat. The reversibility of the process has been studied by van Bemmelen (20, 25), who has also shown that the rate at which water is lost on drying over sulphuric acid is not essentially different from the rate at which evaporation takes place from a pure water surface under the same conditions. The separate particles of clay are so small that, when placed in water, they assume a state of Brownian movement and sink only very slowly in spite of their high specific gravity. Traces of electrolytes have a profound effect on these properties: small quantities of acids or salts cause the temporary loss of plasticity, impermeability, and the property of remaining long suspended in water without settling; the clay is now said to be flocculated. The change can be watched if a small quantity of any flocculating substance is added to the turbid liquid obtained by shaking clay with water; the minute particles are then seen to unite to larger aggregates which settle, leaving the liquid clear. There is, however, no permanent change, deflocculation takes place and the original properties return as soon as the flocculating agent is washed away. Alkalis (caustic soda, caustic potash, ammonia and their carbonates) produce the reverse effect: they deflocculate clay, intensifying its stickiness and impermeability and causing it to remain suspended in water for long periods¹ (see p. 161).

Clay is thus an electro-negative colloid, its reaction probably being conditioned by a trace of potash liberated by hydrolysis.

Further, it appears to act as a semipermeable membrane in relation to the movement of water:² this property might

¹ Leoncini and Masoni (172) were unable to find that the modification in permeability in soil caused by saline solutions had any relation to their powers of flocculating clay.

² Lynde, *J. Phys. Chem.*, 1912, 16, 759-778, and *J. Amer. Soc. Agron.*, 1913, 5, 102-106.

cause some peculiarities of behaviour on sandy soils, such as the Bagshot beds, where there are thin partings of clay.

A remarkable change sets in when clay is sufficiently heated, and it permanently loses all its special properties.

Several theories have been put forward to account for the special properties of clay, and in particular its plasticity. It has often been assumed that these properties are the necessary result of the smallness of the particles, which brings into prominence the surface forces. Rohland¹ attributes plasticity to hydrated colloidal substances forming a gelatinous film round the clay particles, and Le Chatelier² to minute flake-like particles. At present the evidence is insufficient to allow of discrimination.³

These clay properties are of great importance to the fertility of the soil, and no constituent is more necessary in proper proportions, or more harmful in excess. Clay impedes the movement of water in the soil and keeps it in the surface layers within reach of the plant roots, thus making the soil retentive of water. Excess of clay, however, interferes too much with the water movements, making the soil waterlogged in wet weather and parched in dry seasons even though the permanent water level is near the surface; it also impedes the movement of air to the roots and lowers the temperature of the soil. The adhesive properties of clay cause the soil particles to bind together into those aggregates on which "tilth" depends; soil without clay would be very like a sand heap. Here also, however, excess of clay does harm and makes the soil so adhesive that it sticks to the tillage implements and retards their movements; it also tends to form large clods unfavourable to vegetation. These effects are intensified in wet weather; the soil becomes sticky or "poached" and must not be worked or the tilth is injured for a long time. Another effect of a large amount of clay is to make the soil shrink very much on drying, so that large cracks appear in the fields in summer time. These harmful

¹ P. Rohland, *Die Tone* (Vienna), 1910.

² *La silice et les silicates*. Paris, 1914.

³For discussion see A. B. Searle, *British Clays, Shales, and Sands*, 1912

effects are reduced by flocculation effected by dressings of lime or chalk (which become converted into calcium bicarbonate in the soil) and by organic matter; on the other hand, they are intensified by the deflocculation resulting from the use of alkaline manures like liquid manure, or by sodium nitrate, which leaves a residue of sodium carbonate in the soil. Further, as pointed out above, clay "fixes" and retains the ammonia and potash supplied as manure. In general 8 to 16 per cent. is a satisfactory proportion of clay in a soil where the rainfall is 20 to 30 inches per annum.

Fine silt (0.01 to 0.002 mm. in diameter) has also great water-holding power, and in excessive amounts (above 10 to 15 per cent.) it increases the difficulty of working the soil, especially if much clay is present. It does not possess the marked plastic and colloidal properties of clay, it behaves differently towards electrolytes (see p. 162) and is less altered by lime; indeed no method is known for making it tractable. It is usually less in amount than the clay; certain peculiarities in cultivation are in some cases manifested where the reverse obtains, e.g. in the Lower Wealden strata, the Upper Greensand and the Lincolnshire warp lands; in North Wales, however, many soils possess more silt than clay without any apparent disadvantage.

The coarser grade of *silt* (0.04 to 0.01 mm. in diameter) appears to be very valuable, and constitutes 30 to 40 per cent. of many of the loams most famous in the south-east of England for carrying their crops well and not drying out. The fertile loess soils of the United States are also rich in silt, containing 55 or more per cent. of material of .05 to .005 mm. diameter.¹ Light, sandy loams, on the other hand, may contain only 10 to 20 per cent.; some of these are highly fertile, but as a rule they require large dressings of dung, or a situation favourable for water-supply. Probably silt plays a very important part in maintaining the even conditions of moisture so desirable for plant growth. It is fine

¹ J. G. Mosier and A. F. Gustafson, *Soil Physics and Management*, 1917 p. 64.

enough to retard, but not to prevent, percolation, and it facilitates capillary movement of water.

Fine sand (0.2 to 0.04 mm. in diameter) forms a considerable fraction—usually 10 to 30 per cent. or more—of nearly all soils. Although its dimensions are relatively large, it still possesses cohesiveness and a tendency to cake together; it has not, however, so great an effect as silt in maintaining a good moist condition. Soils containing 40 per cent. or more of fine sand tend to form, after rain, a hard crust on the surface, through which young plants can only make their way with difficulty until it has been broken by a roller. But they have no great water-holding capacity or retentive power, and are not infrequently described by their cultivators as hungry soils that cannot stand drought. The notoriously infertile Bagshot sands and the barren Hythe beds in West Surrey are largely composed of this fraction, as much as 70 per cent. being sometimes present. In all these cases, however, clay is deficient and the situation is dry; better results are obtained when the clay exceeds 8 or 9 per cent., or when the water table is near the surface, especially if the amounts of coarse sand and gravel are not too high.

Coarse sand (1 to 0.2 mm. in diameter) is perhaps the most variable of all soil constituents in amount, and, as its properties are in many ways the reverse of those of clay, it exercises a very great effect in determining fertility. Through its lack of cohesion it keeps the soil open and friable; in moderate amounts it facilitates working, but in excess it increases drainage and evaporation so much as to interfere seriously with the water-holding capacity of the soil. Many good loams contain less than 4 per cent., and in general strong or tenacious soils contain less coarse sand than one-half the quantity of clay present. When the coarse sand exceeds the clay in amount the soil becomes light, unless of course the clay is above 20 per cent., when the soil must always remain heavy. Not being a colloid, it possesses no power of absorbing water or soluble salts. Soils containing 40 per cent. or more of coarse sand and less than 3 per cent. of clay

are cultivated only where large quantities of dung are available, or where the water-supply is exceptionally good. As the amount of coarse sand increases, the soils become less and less suited to cultivation, till finally the sand dune condition may be reached, though in adequately moist conditions cultivation may still continue even when 90 per cent. of coarse sand and no clay are present (*e.g.* part of Anglesea).

Fine gravel is not usually present to any great extent, and is of importance only when the coarse sand is already dangerously high. Stones cannot be determined quantitatively by any method of sampling in use, and their effect must be judged by a visit to the field. If they are uniformly scattered through a stiff soil, as in the Clay-with-Flints, they are on the whole beneficial, because they facilitate tillage. Where they form a bed underlying the soil they may do harm by causing over-drainage. Some typical examples are discussed in Chapter VII.

Reactive Inorganic Constituents.

It was formerly supposed that zeolites occurred in the soil and accounted for many of the soil reactions and absorptions. The direct evidence is so slight that this view is now generally given up. It seems necessary, however, to assume that some of the inorganic constituents of the soil are very reactive, since certain chemical changes are brought about which can hardly be attributed to micro-organisms. Thus, calcium cyanamide is decomposed by soil with formation of urea, and the change proceeds whether the soil be fresh or ignited; this change can also be effected by certain minerals, *e.g.* prehnite. So phenol reacts instantly with soil to form some insoluble compound not decomposable by steam. These obscure reactions are being studied at Rothamsted (p. 215).

Soil Acidity.

It has long been known that many soils are acid to litmus paper but become neutral on addition of lime or calcium

carbonate. Many cultivated plants, notably clover and its allies, fail to grow well on such soils, and they succeed only after lime has been added: *Azotobacter* and other organisms are also adversely affected (p. 239).

The older chemists took the simple and obvious view that these soils contained an acid or acids, and, as "high moor" peat showed the same property, they concluded that the acid was of the same general nature in both cases. It was assumed that plant residues at a certain stage in their decomposition formed some acid substance which accumulated in circumstances where decomposition became very slow, *e.g.* in badly drained and badly aerated soils.

But instances were observed of acid soils, well drained and therefore not suffering from slowness of decomposition, containing so little organic matter that it was difficult to attribute acidity to organic compounds. It was therefore necessary to assume the presence of acid mineral substances in the soil, and a number of investigations were made showing that kaolin and similar silicates, which might be expected to occur in soil, become more and more acid to litmus paper on treatment with CO_2 solution.¹

Chemical hypotheses, satisfactory as they might otherwise have been, suffered from the serious drawback that no one was ever able to isolate an undeniable acid from soils in any significant quantity. A wholly different hypothesis was therefore put forward by Cameron. Setting out from van Bemmelen's demonstration that humus is a colloid he showed that all the phenomena of soil acidity could be explained as simple colloidal manifestations and did not require the assumption of soil acids at all. It was only necessary to suppose that the soil colloids absorbed the base more readily than the acid from blue litmus and the whole phenomena are explained. In support of this view Cameron showed that cotton and other absorbents behaved exactly like "acid" soils, slowly turning blue litmus red; the phenomenon was therefore a general property of a class of absorbents.

¹ See Gans (101) for a review of the literature of this problem.

Baumann and Gully (106) applied this idea to the case of peat and showed that it fully explained all the facts then known.

In the first instance they pointed out that it was not necessary to assume that the "acid" was a decomposition product because the original sphagnum was almost as "acid" as the peat.

Secondly, the acid if it exists must be insoluble because the water extract of the peat is practically neutral to litmus.

It must, however, be very potent, because solutions of neutral salts such as calcium chloride, sodium nitrate, etc., are decomposed with liberation of free hydrochloric and nitric acids when treated with peat or sphagnum.

Baumann and Gully argue that no acid of this character is known to chemists, and it involves less strain to conceive of a physical absorption of the base from the dissolved salt with liberation of the acid than to imagine an insoluble organic acid capable of decomposing simple salts in solution.

Further reasons for supposing that the phenomena are due to absorption and not to chemical action are:—

1. The amounts of acid liberated from equivalent quantities of different salts of the same base are not equal as they should be in a chemical action.
2. The amounts of base absorbed are not equivalent, *e.g.* potassium is absorbed to a greater extent than sodium.
3. The amount of action varies with the concentration of the solution and the mass of the sphagnum, but not in the way that would be expected of a chemical change.
4. The electrical conductivity of peat is very low, much less than that of an acid having the same solvent action on tricalcic phosphate.

The view that acidity of the mineral acid soils is due to preferential absorption of the base was developed by Harris (124) in an investigation of Michigan soils. The phenomena are substantially the same as for peat: the soil turns blue litmus red: an aqueous extract is neutral: but an extract

made with a solution of a salt, *e.g.* calcium nitrate, is acid. We must therefore assume either an insoluble but very potent mineral acid, or a preferential absorption of the base over the acid. The latter is indicated because, as in the case of peat, the amount of acid liberated from equivalent quantities of different salts is not the same, as it should be in a chemical reaction.

Daikuhara (74*b*) has applied this view to the case of the acid mineral soils of Japan and Korea, but he has modified the explanation and made it more easily intelligible to the chemist, who finds it difficult to understand why an unparalleled physical decomposition of a simple salt should be accepted, and the assumption of a difficultly soluble but potent acid rejected. Daikuhara shows that the development of acidity in the salt solution is due to an exchange of bases and not to simple absorption of the base from the salt. If the acid solution is analysed it is found to be really a solution of an aluminium salt: aluminium being given up from the soil in amount approximately equivalent to the base absorbed. Aluminium salts, as is well known, turn blue litmus red and therefore are indicated as acids. The phenomenon is still essentially an absorption, but the seat of the reaction is located.

This view is supported by Rice's experiments (238) which have demonstrated the substantial identity in hydrogen ion concentration of a solution of aluminium nitrate and the solution obtained by treating an "acid" soil with potassium nitrate solution. Hartwell and Pember (128*a*) also support this view by an ingenious line of argument. True acids added to nutrient solutions affect barley and rye in water culture similarly, while extracts of acid soils affect them differently. Therefore acid soil extracts contain something not present in acid solutions; on testing they were found to contain aluminium. The effect of aluminium salts on plant growth was examined¹:

¹ J. B. Abbott, S. D. Conner, and H. R. Smalley had previously attributed the infertility of an Indiana soil to the presence of aluminium salts (*Ind. Exp. Sta. Bul.*, 170, 1913).

and found to resemble that of the acid soil extract. Mirasol¹ has confirmed and extended these observations.

Ramann also adopts this physical hypothesis and gives up the expression "acid soils," using instead "absorptiv ungesättigte Boden". Kappen² confirms the observations without entirely accepting the explanation.

Recent work shows that both views have a foundation of truth; there are at least two causes at work: lack of bases in the soil brings about the absorption phenomena discussed above, but there are also true acids present in soil under certain conditions. Rindall of Helsingfors (239), Sven Odén of Upsala (218*a*), Tacke (278), and Ehrenberg and Bahr (93*d*) have each argued in favour of definite humic acids in peat (see p. 139). Truog (285) finds, in the case of mineral soils, that equivalent amounts of different bases are required to neutralise the acid properties of the soil—which if generally true would be easier to explain by assuming an acid than an adsorption.

The view that soil acidity is caused by actual acids has gained support from recent work³ on the hydrogen ion concentration in soils.

Chemists study acids in two ways:—

1. By measuring the hydrogen ion concentration, a value based on the assumption that an acid on solution in water dissociates into two parts, called ions—one being hydrogen, and the other the rest of the molecule.

2. By determining the titration value, *i.e.* the number of cc. of standard alkali solution which a given volume of the acid solution will neutralise. In the language of the dissociation hypothesis this value measures the total quantity of hydrogen ions producible under the conditions of the experiment, supposing them to be neutralised or linked up with $-OH$ ions as quickly as they are liberated.

¹ *Soil Sci.*, 1920, **10**, 153.

² H. Kappen, *Studien an saurem Mineralboden aus der Nahe von Jena (Landw. Versuchs-Stat.*, 1916, **88**, 13-101).

³ For a critical summary of recent work see E. A. Fisher, *J. Ag. Sci.*, 1920, **11**, 19.

The titration value measures the quantity of the acid but it makes no distinction between a strong acid, such as sulphuric acid, and a weak acid, like acetic acid: the great difference in action on plant life exhibited by the two acids is missed altogether. Moreover, the titration value is not an absolute constant; polybasic acids, which are by far the most numerous, have several titration values, according to whether one, two or more of the hydrogen atoms are affected. Different indicators, therefore, give different numerical results. So long as the constitution of the acid is known this does not matter, but it causes complications in dealing with a mixture of unknown acids.

Many of the methods suggested for measuring soil acidity, including all the "lime requirement" methods, afford a more or less rough measure of the titration value¹: the differences in results are partly due to absorptions and partly to differences in the number of hydrogen atoms concerned.

The determination of the hydrogen ion concentration, *i.e.* of the ions actually present, as distinct from those that would finally be liberated on neutralisation, is an attempt to measure the intensity of the acid as distinct from its quantity. The principle of the method is simple in dealing with solutions of pure acids: it is based on the ordinary dissociation law: $\frac{H^+ \times X^-}{HX} = K$ where H^+ and X^- are the ions produced on the dissociation of the acid HX , and K is a constant. The number or the concentration of the ions is measured by the electrical conductivity of the solution, but once this has been determined for a given acid it can become a standard against which the hydrogen ion concentrations of other acids can be rapidly compared by means of a set of indicators.²

The problem becomes more complex when salts are present, because the additional ions thus introduced affect the

¹ Probably all the results are too high, as they include the absorptions. See H. R. Christensen (67b), also 105c.

² A useful account of the measurement of the hydrogen ion concentration is given by J. F. McClendon in *Physical Chemistry of Vital Phenomena* (1917), which was written for biological students.

amount of dissociation: in particular they make it difficult for the hydrogen ion concentration to increase when another acid is added. Colloidal substances act in the same way. This effect, known as "buffer action," is of great importance in vital phenomena and is well marked in the case of soils. Thus if an acid is added to soil the increase in the hydrogen ion concentration is not nearly so great as if the same quantity of acid were added to water.

The numerical values of the hydrogen ion concentrations are rather unmanageable and a convention has therefore been adopted in dealing with them.

In pure water or in a neutral solution

$$H^+ = OH^- = 1 \times 10^{-7.07} \text{ gram-ions per litre.}$$

Acidity means a hydrogen ion concentration in excess of that of water, *i.e.* the index instead of being -7.0 is greater: as the quantity is negative this means that the number itself is less: it may fall to zero. Simple trial will show that it is very difficult to plot on the same curve numbers ranging from 1 to 1×10^{-7} . A further complication began to arise but fortunately was checked: investigators expressed their results in terms not of 1, but of some other number, multiplied by 10 to some negative power, *e.g.* one solution might be represented by the value 4.4×10^{-6} , and another by 6.8×10^{-7} , and it was rather difficult to make a comparison.

To overcome the first of these difficulties Sørensen¹ adopted the familiar device of plotting the logarithms of the numbers instead of the numbers themselves; and to overcome the second he reduced all to terms of $1 \times$ some power of 10: thus the two cases just quoted become $1 \times 10^{-5.36}$ and $1 \times 10^{-6.17}$ respectively. He calls the numbers 5.36 and 6.17 the P_H values of the solutions: in reality they are the values for the $-\log(H^+)$. On this notation the P_H value for neutrality is 7.07; that for acidity is anything less—down to nothing—that for alkalinity is anything greater—up to 14.14.

¹ S. P. L. Sørensen, *Biochem. Zeitsch.*, 1909, **21**, 130, and **22**, 352; see also *Ergebnisse d. Physiologie* (Asher and Spiro), 1912, **12**, 393.

In consequence of the buffer action already mentioned these values are not liable to disturbance by small additions of substances to the soil.

A large number of determinations of the P_H or $-\log(H^+)$ values for American soils have been made by Gillespie (105*a*) and G. Sharp and D. R. Hoagland (260), while for British soils a beginning has been made in the Rothamsted laboratories. Some of the values are as follows:—

| | American Soils. Sharp and Hoagland. | British Soils. |
|---------------------------------------|--|----------------|
| Acid soils, extreme value | 3.7 | 4.6 |
| Fertile soils | 7.04-7.52 | |
| Alkaline soils, extreme value | 9.7 | |

The acidity of root sap is of the order of 5.5-6.8 (p. 81).

The relatively small range of variation in comparison with the large variation in amount of titratable acidity is explained by the buffer action described above.

In addition to and probably distinct from this natural acidity it is possible to induce acidity in soils deficient in calcium carbonate by the long-continued application of ammonium sulphate. This was first observed by Wheeler in Rhode Island (303) and it is demonstrated in a remarkable manner at the Royal Agricultural Society's Experiment Station at Woburn. Apparently this is not the same as "acidity" liberated by solutions of neutral salts in acids, because ammonium sulphate appears to act specifically, no other fertiliser behaving in this manner at Woburn.¹

Hall supposes, with considerable probability, that the ammonia is taken up by the plant, leaving the sulphuric acid in the soil, and this view seems justified by the fact that nitrate of soda behaves altogether differently, leaving an alkaline residue in the soil.

¹ There are a few cases on record where potassium salts are said to have reduced yields, and here it is possible that acid substances have been liberated by the dissolved salt.

TABLE XXXI.—EFFECT OF CALCIUM CARBONATE ON THE TEXTURE OF SOILS.

| | Hamsey Green. | | Rothamsted. | |
|-----------------------|---------------|------------------------|-------------------------|-----------------------------------|
| | Arable Soil. | Too Sticky for Arable. | Arable Soil, Barnfield. | Too Sticky for Arable, Geescroft. |
| Fine gravel . . . | 1.7 | 1.6 | 2.4 | 1.8 |
| Coarse sand . . . | 5.3 | 9.5 | 5.5 | 4.9 |
| Fine sand . . . | 28.7 | 22.3 | 20.3 | 27.8 |
| Silt . . . | 26.3 | 25.4 | 24.4 | 25.4 |
| Fine Silt . . . | 10.2 | 9.9 | 12.7 | 10.6 |
| Clay . . . | 16.4 | 16.0 | 22.0 | 19.0 |
| Loss on ignition . . | 4.8 | 5.2 | 4.7 | 5.1 |
| Calcium carbonate . . | 1.02 | .48 | 3.0 | .16 |

The present position may be summarised as follows :—

The existence of a hydrogen ion concentration greater than that of water is satisfactory evidence of the presence of true acids in soils. The measurements at present throw no light on the nature or quantity of the acids. The acids may be—

- (a) Organic,
- (b) Siliceous,
- (c) Formed by hydrolysis of iron or aluminium salts.

They may adversely affect plants or micro-organisms by reason of their strength or their quantity. On the other hand, the acids themselves may be without serious action (see p. 81). The special properties of an "acid soil" may result from a lack of basicity, whereby—

1. Special absorption relationships appear ;
2. Lack of calcium may affect plants or micro-organisms ;
3. Certain toxic substances, *e.g.* metallic salts, may remain effective, which in presence of lime would be thrown out of action ;
4. The clay may become deflocculated and therefore assume a sticky condition unfavourable to plant growth.

Table XXXI. shows pairs of soils similar in constitution and in general external conditions, temperature, water-supply,

etc., but very different in agricultural value because of their different content of calcium carbonate, one being readily cultivated while the other is wet and sticky, and suitable only for pasture land.

"Sourness" of Soil: Its Relation to Acidity and Calcium Carbonate.

Soils which are infertile from lack of calcium carbonate are called "sour" by farmers. The older chemists substituted the word "acid," but, as shown above, the effect is not necessarily in all cases attributed to acids, and therefore it seems desirable to retain the farmers' term as the broad one and distinguish between "sourness" due to acidity and that due to lack of basicity.¹

Whatever its cause in a given case sourness can be overcome by addition of lime or calcium carbonate; soils containing calcium carbonate are never sour, and they are generally fertile.

It by no means follows, however, that soils devoid of calcium carbonate are infertile. Hendrick and Ogg at Aberdeen (132) and Robinson in N. Wales (240) have both described soils free from calcium carbonate but fertile and indeed neutral in reaction: Hoagland observes² that certain Californian soils with low P_H value, *i.e.* considerable intensity of acidity, and large "lime requirements," are nevertheless able to produce excellent crops of many types.

In the present state of our knowledge it is hardly possible to say from chemical examination of the soil alone whether it is "sour" or not, *i.e.* whether it is or is not infertile through lack of calcium carbonate. A combination of chemical analysis and field observation, however, enables something to be done: soils known by vegetation observations to be comparable can

¹ This seems preferable to the distinction made by some of the investigators between "positive acidity" caused by actual acids, and "negative acidity" caused by adsorption of base (*cf.* Lyon, *Soils and Fertilisers*, p. 112. See also H. R. Christensen, *Soil Sci.*, 1917, 4, 115, and C. J. Schollenberger, *Soil Sci.*, 1917, 3, 279).

² Private communication to the author.

be set out in order of their calcium carbonate content by the usual analytical methods, or of their lack of calcium carbonate by one of the lime requirement methods.¹ Before any indication can be given of the amount of lime required for cultivation it is necessary to make field trials (p. 335).

In general, sandy soils require only sufficient calcium carbonate to prevent sourness, while clay soils need in addition enough to keep the texture good. Sands well supplied with calcareous water and under ordinary arable cultivation may get along with 0.1 per cent. or even less calcium carbonate. Many light soils that are intensively farmed respond to dressings of chalk or of ground limestone, even though 0.2 or 0.3 per cent. is already present. 0.5 per cent. of calcium carbonate commonly proves insufficient for clay soils, and even 1.0 per cent. may not be enough in highly-farmed districts, especially where cattle are fed on the land and tread the soil into a somewhat sticky state. Further increases in calcium carbonate over and above the proper amount are not known to have any effect except to provide a margin of safety. Considerable work has been done on the effect of lime on peat soils, which seems to be more than a neutralisation of acidity. Odén (218*e*) suggests that the calcium humate produced may be directly beneficial to plants.

Calcium carbonate is not a permanent constituent of the soil, but changes into the soluble bicarbonate and washes out into the drainage water; the average loss per acre per annum throughout England and Wales has been estimated at 500 lb., and at Rothamsted on the arable land at 800 to 1000 lb. (120*b*). The rate of loss is influenced by the treatment, being increased by the use of ammonium sulphate and decreased by dung and by a growing crop; it is much less on pasture than on arable land. Repeated additions of calcium carbonate to

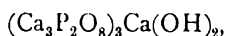
¹ Such as Veitch's (287) or Hutchinson and McLennan's (140*d*). L. J. Wild, *J. Ag. Sci.*, 1917, 8, 154, shows that the latter when modified by a correction factor of 0.1 per cent. proves helpful in the study of New Zealand soils. For a critical account of the various methods see Ames and Schollenberger (4) and E. A. Fisher (99). It is hardly necessary to point out that the "lime requirement" measures something entirely distinct from the P_H value (p. 115).

the soil are, therefore, necessary : indeed, chalk and lime are among the oldest of manures. Soils lying immediately above chalk and limestone are no exceptions, and in wet regions they may become thoroughly decalcified.

On chalk soils the percentage of calcium carbonate may rise very high, and then a wholly new set of properties comes in. It is impossible to draw any exact line showing where these properties begin to appear, but they entirely mask the effects of the silica and silicate particles and obliterate the distinctions between sands, loams, clays. Chalk soils, therefore, form a class by themselves to which the ordinary laboratory methods of analysis and investigation do not apply : unfortunately, appropriate methods have not yet been worked out.

The Phosphorus, Potassium, and Calcium Compounds of the Soil.

Part of the phosphorus in the soil is probably present in organic combinations derived from plant or animal residues : this has been investigated by Vincent,¹ by Potter and Snyder² and by Schollenberger ;³ none of whom, however, were able to effect identification of the compounds. Part, however, is in inorganic combination and Bassett has shown⁴ that it most probably occurs as hydroxyapatite—



this being the solid phase stable over a range extending from faintly acid to alkaline conditions : any phosphate such as superphosphate or basic slag added to the soil as fertiliser would tend to be converted into this substance.

The potassium compounds in the soil are probably silicates. Their distribution has been studied by Dumont⁵ who found that they may occur in the finer or coarser portions of the

¹ *Compt. Rend.*, 1917, **164**, 409.

² *Soil Sci.*, 1918, **6**, 321-332.

³ *Ibid.*, 365-395 ; 1920, **10**, 127. In this case about one-third of the phosphorus occurred in organic combination.

⁴ *Trans. Chem. Soc.*, 1917, **III**, 620-642.

⁵ *Compt. Rend.*, 1904, **138**, 215-217.

soil with very different effects in either case. He instances two soils of nearly equal potash content, one of which from la Creuse responds to potassic fertilisers, while the other from Grignon does not: in the former case the potash is present mainly in the coarser material, in the latter mainly in the fine (Table XXXII.).

TABLE XXXII.—DISTRIBUTION OF POTASH AMONG SOIL PARTICLES (DUMONT).

| | Per cent. of K ₂ O in Soil. | Response to Potassic Fertilisers. | Per cent. of "Argile". | Per cent K ₂ O in Argile | Percentage Distribution of Potash in Soil. | | |
|-----------|--|-----------------------------------|------------------------|-------------------------------------|--|------------|---------|
| | | | | | Sable Grossier. | Sable Fin. | Argile. |
| Grignon . | 0.85 | Nil | 16.8 | 0.94 | 16.6 | 65.8 | 17.7 |
| La Creuse | 0.89 | Good | 4.5 | 0.51 | 70.9 | 26.4 | 2.7 |

The calcium compounds of a number of soils have been studied by E. C. Shorey, Fry and Hazen (263). The following were detected by petrographic methods:—

Frequently—

Hornblende, chiefly $\text{Ca}(\text{MgFe})_2\text{Si}_4\text{O}_{12}$ with $\text{Na}_2\text{Al}_2\text{Si}_4\text{O}_{12}$ and $(\text{MgFe})_2(\text{AlFe})_4\text{Si}_2\text{O}_{12}$.

Plagioclase, isomorphous mixtures of $\text{CaAlSi}_2\text{O}_8$ and $\text{NaAlSi}_3\text{O}_8$.

Epidote, $\text{Ca}_2\text{H}(\text{AlFe})_2\text{Si}_3\text{O}_{13}$.

Occasionally—

Calcite, CaCO_3 .

Titanite, CaTiSiO_5 .

Garnet $(\text{Ca}, \text{Mg}, \text{Fe}, \text{Mn})_3(\text{Al}, \text{Fe}, \text{Cr}, \text{Ti})_2(\text{SiO}_4)_3$.

Rarely—

Dolomite $(\text{Ca}, \text{Mg})\text{CO}_3$.

Augite, $\text{CaMgSi}_2\text{O}_6$ with $(\text{Mg}, \text{Fe})(\text{Al}, \text{Fe})_2\text{SiO}_6$.

Gypsum, $\text{CaSO}_4 + 2\text{H}_2\text{O}$.

Chemical analysis showed that pairs of soils containing the same total CaO might differ considerably in their content of the various calcium compounds (Table XXXIII.):—

TABLE XXXIII.—CALCIUM COMPOUNDS IN SOIL (SHOREY, FRY & HAZEN (263)).

| Soil No. | Total CaO. | CaCO ₃ . | CaO as:— | | |
|----------|------------|---------------------|-------------------------------------|--|-----------------------|
| | | | Easily Decom- posable Silicates. | Difficultly De- composable Silicates. | Humus Combination. |
| 58 | 5.37 | 2.50 | 0.54 | 2.33 | Nil |
| 61 | 4.64 | 0.06 | 0.11 | 4.34 | 0.13 |
| 24 | 1.98 | 0.12 | 0.02 | 1.84 | Nil |
| 36 | 1.92 | 0.49 | 0.34 | 0.98 | 0.11 |

The Soil Water or Soil Solution.

The soil retains by absorption and surface attractions some 10 to 20 per cent. of its weight of water, distributed as films over its particles. This water is of obvious importance as the medium through which plants and micro-organisms derive their food; indeed, it may be regarded as the culture solution for the plant. Its relationship to the mineral matter is discussed by Cameron (65*c*, *d*, and *e*) and the displacements of equilibrium under the influence of climate, plant roots, etc., by Nolte (216). Several methods have been used for extracting the solution in order to determine its composition.

As often happens the pioneer work was done in France: Schloesing in 1866 (245*e*) devised a method which is still often used—displacement of the soil solution by means of water.

Displacement Methods.—Schloesing placed 30-35 kgms. of freshly taken soil in a large inverted tubulated bell jar and poured on it water coloured with carmine, this being done to simulate the action of rain. The added water at once displaced the soil water and caused it to descend so that it could be collected: a sharp horizontal line of demarcation between the added and the original water persisted throughout the experiment even when 8 days were occupied in the descent. A typical analysis of the displaced liquid in milligrams per litre was:—

| SiO ₂ . | Nitric Acid. | Carbonic Acid. | CaO. | MgO. | K ₂ O. | Na ₂ O. | Sulphuric Acid. | Chlorine. | Organic Matter. |
|--------------------|--------------|----------------|------|------|-------------------|--------------------|-----------------|-----------|-----------------|
| 29.1 | 3.05 | 11.8 | 26.4 | 13.5 | 6.9 | 7.8 | 57.9 | 7.4 | 37.5 |

and in addition traces of phosphorus and of ammonia. This soil contained 19.1 per cent. of water.

The total concentration is seen to be about .08 per cent.

Gola (108) also adopted the artificial rain device but the addition of water ceased as soon as a regular flow from the soil had set up: the soil was then allowed to drain for some 36 hours; the solution thus obtained was called the "pedolytic" solution. Finally, the water was squeezed out by a screw press; this was called the "pedopiezic" solution. The total concentration varied in different soils from 2 per cent. down to 0.2 per cent. or less, the lower amounts being from soils corresponding to normal agricultural soils (see p. 237). The weak point in the method is that the added water may upset some of the adsorption relationships of the soil and thus vitiate the results. Itscherekov¹ substituted methyl or ethyl alcohol; van Suchtelen² used paraffin oil; J. F. Morgan (203) improved on this by using paraffin oil under pressure and obtained a solution containing 0.04 to 0.13 per cent. of total solids. Some of his analyses are given in Table XXXIV.:

TABLE XXXIV.—COMPOSITION OF SOIL SOLUTION (OIL DISPLACEMENT).
J. F. MORGAN (203).

| Nature of Soil. | Moisture in Soil. | Parts per million in Soil Solution. | | | | Parts per million in Oven-Dried Soil. | | | |
|-----------------|-------------------|-------------------------------------|-------------------|-------|------|---------------------------------------|-------------------|-------|------|
| | | K. | PO ₄ . | Ca. | N. | K. | PO ₄ . | Ca. | N. |
| Fine sand | 29.74 | 24.1 | 5.2 | 30.6 | 3.1 | 7.2 | 1.5 | 9.1 | 0.9 |
| Loam . | 37.8 | 71.1 | 12.2 | 68.2 | 3.2 | 27.0 | 4.6 | 25.9 | 1.2 |
| Clay . | 24.5 | 44.8 | 4.6 | 42.9 | 6.6 | 11.0 | 1.1 | 10.6 | 1.6 |
| Peat . | 132.9 | 50.1 | 2.5 | 183.8 | 17.1 | 94.9 | 3.4 | 244.3 | 22.7 |

¹ *Russian J. Expt. Ag.*, 1907, 8, 147-165.

² *J. fur Landw.*, 1912, 60, 369.

The clay also contained 32.6 parts of magnesium in the dried soil and 132.3 in the solution.

A more rapid, but less accurate method of obtaining a soil solution has been adopted by the United States Bureau of Soils. The soil is stirred up with water and filtered under pressure through a Chamberland filter. The results are taken to indicate the following average composition of the soil water:—

| PO ₄ | NO ₃ | Ca | K |
|-----------------|-----------------|-------|---|
| 7.64 | 5.47 | 11.67 | 22.74 per million of dry soil. ¹ |

A *centrifugal method* was used by Whitney and Cameron (305a) with the results given in Table XXXV.:—

TABLE XXXV.—COMPOSITION OF SOIL SOLUTION (CENTRIFUGAL METHOD).
WHITNEY AND CAMERON (305a).

| | Soil Solution, parts per million. | | | | Dry Soil, parts per million. | | | |
|-----------------------------|--------------------------------------|-----------------|-------|-------|---------------------------------|-----------------|------|------|
| | PO ₄ | NO ₃ | Ca. | K. | PO ₄ | NO ₃ | Ca. | K. |
| Sassafras loam, New Jersey— | | | | | | | | |
| Wheat, good | 7.20 | 7.20 | 44.40 | 33.60 | 1.35 | 1.35 | 8.34 | 6.31 |
| " poor | 7.00 | .40 | 26.90 | 24.40 | 1.40 | .08 | 5.38 | 4.88 |
| Leonardtown loam, Maryland— | | | | | | | | |
| Wheat, good | 6.30 | 1.44 | 16.20 | 21.60 | 1.38 | .32 | 3.56 | 4.75 |
| " " | 8.40 | 4.08 | 21.60 | 38.40 | 1.48 | .72 | 3.80 | 6.75 |
| " poor | 9.75 | 4.80 | 8.50 | 19.25 | 2.45 | 1.21 | 2.12 | 5.10 |

The method, however, is difficult in application and has not come into general use.

Pressure methods have been adopted by several investigators. In Ramann's (233c) laboratory 3 kilos of soil were subjected to a pressure of 300 kilos per sq. cm. The amounts of calcium and of potassium were found to vary considerably in different extracts obtained from the surface soil, the proportions relative to the other constituents increasing as the solution became concentrated by dry weather and falling as the solution became diluted by rain. In extracts prepared

¹ The Bureau of Soils prefers to express the compositions in terms of dry soil rather than of solution.

from the subsoil, on the other hand, the amount of calcium showed less variation, except only for a rise at midsummer. There was evidence of a transportation of calcium and potassium from the subsoil to the surface during a prolonged period of drought. No indication was obtained, however, that soil adsorption exercised any regulating effect on the concentration of the soil solution; an exchange of bases took place only when the proportions between the dissolved substances were altered.

In van Zyl's experiments (323) the concentration of the solution obtained also varied according to manurial treatment and season of the year, but the percentage composition of the ignited dry matter of the extract remained constant; this being the reverse of what Ramann obtained.

A steel plunger was used by C. B. Lipman.¹

An *absorption method* used by Briggs and McCall consists in driving a Pasteur Chamberland filter into the soil and connecting it with an exhausted 2-litre bottle.²

A totally different method is adopted by Bouyoucos who studies the changes in the soil solution *in situ* by determining the changes in the freezing-point (49c). He finds the osmotic pressure varies between 0.2 to 1 atmospheres in moist soils, and 4.5 to 16.5 at low percentages of moisture. The concentration of the extracted solution was 0.04 to 0.18 per cent. in moist soils and 0.9 to 3.0 per cent. in drier soils.

Some of his results are given in Table XXXVI.

Hoagland and Sharp (136b) have applied the method to Californian soils with interesting results.³ They find no evidence that the soil water is a saturated solution: on the contrary, it appears to be dilute, probably containing less total dissolved matter than the soil extract, and it varies in concentration with the conditions: in their experiments the range

¹ *Univ. California Pubn. Ag. Sci.*, 1918, 3, 131.

² L. J. Briggs and J. R. McCall, "An Artificial Root," *Science*, 1904, 20, 566-569; *Bull.* 31, Bureau of Soils, 1901.

³ For further results see J. C. Martin and A. W. Christie, *Journ. Ag. Res.*, 1919, 18, 139.

TABLE XXXVI.—CONCENTRATION AND OSMOTIC PRESSURE OF SOIL SOLUTION (BOUYOUCOS, 49c).

| | Washington Sand (25). | | Wisconsin Superior Clay (26). | | Wisconsin Carrington Silt Loam (27). | | Wisconsin Carrington Silt Loam (28). | | Wisconsin Miami Silt Loam (29). | | Wisconsin Miami Silt Loam (30). | |
|--|-----------------------|-------|-------------------------------|-------|--------------------------------------|-------|--------------------------------------|-------|---------------------------------|-------|---------------------------------|-------|
| Percentage of moisture | 4.44 | 24.10 | 18.85 | 39.40 | 12.52 | 32.74 | 11.36 | 31.86 | 8.86 | 36.07 | 7.21 | 30.41 |
| Freezing-point depression | .630 | .116 | 1.200 | .017 | 11.248 | .043 | .689 | .035 | .86 | .029 | 1.080 | .029 |
| Parts per million dry matter in soil extract | 15,370 | 2,829 | 29,268 | 415 | 30,440 | 1,049 | 16,800 | 854 | 19,560 | 707 | 26,340 | 707 |
| Osmotic pressure of soil solution: atmospheres | 7.590 | 1.399 | 12.28 | .205 | 14.80 | .518 | 8.300 | .422 | 9.659 | .350 | 13.00 | .350 |

was generally from 0.1 to 1 atmosphere. The seasonal variations are shown in Fig. 16.

These various methods naturally give different results. The general conclusion, however, seems to be that the solution in a normal agricultural soil contains mainly calcium nitrate and bicarbonate; with some organic matter, sodium, magnesium, silica, chlorine, sulphuric acid, less potassium, a trace of ammonia, and only little phosphate. In ordinarily moist

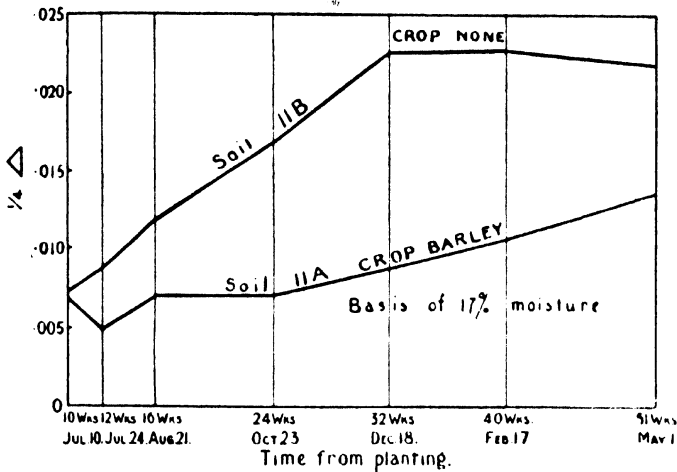


FIG. 16.—Variations in concentration of soil solution with crop and season, showing that the barley crop much lowers the concentration even after its removal in August. On the vertical axis one-quarter of each freezing-point depression is plotted: an approximate estimate of the corresponding osmotic pressure is obtained by multiplying the plotted value by 50 (Hoagland and Sharp, 136b).

soil it has a concentration of the order of 0.1 to 1.0 per cent., or some 0.5 to 5 atmospheres osmotic pressure; this varies however, with the rainfall and the manuring. The proportions of the components also varies, again changing with the season and the manuring. The nitrates are perhaps the most variable constituents, but the calcium and potassium also vary both relatively and absolutely—excepting in van Zyl's experiments.

The numerous analyses of land drainage water that have

been made in this country and on the Continent throw some light on the composition of the soil solution. As might be expected from the known absorptive properties of clay and of humus, drainage water contains mere traces of NH_4 and PO_4 , and only little K; it contains chiefly carbonic acid, SiO_2 , Cl, SO_4 , NO_3 , Ca with some Fe, Mg, and Na. Typical analyses are given in Table XXXVII.

TABLE XXXVII.—ANALYSIS OF DRAINAGE WATERS FROM CULTIVATED FIELDS : PARTS PER MILLION OF SOLUTION.

| | Rothamsted: Broadbalk Field. ¹ | | | Field at Göttingen. ² | |
|--|---|---------|-----------------------|----------------------------------|----------------|
| | No Manure. | Dung. | Complete Artificials. | Highest Result. | Lowest Result. |
| | Plots 3 and 4. | Plot 2. | Plot 6. | | |
| CaO | 98·1 | 147·4 | 143·9 | 184 | 157 |
| MgO | 5·1 | 4·9 | 7·9 | 46·4 | 31·3 |
| K ₂ O | 1·7 | 5·4 | 4·4 | 3·7 | 1·7 |
| Na ₂ O | 6·0 | 13·7 | 10·7 | — | — |
| Fe ₂ O ₃ | 5·7 | 2·6 | 2·7 | — | — |
| Cl | 10·7 | 20·7 | 20·7 | — | — |
| SO ₂ | 24·7 | 106·1 | 73·3 | 59·2 | 43·5 |
| P ₂ O ₅ | ·6 | — | 1·54 | — | — |
| SiO ₂ | 10·9 | 35·7 | 24·7 | — | — |
| N as NH ₃ | ·14 | ·20 | ·24 | — | — |
| N as Nitrate | 15·0 | 62·0 | 32·9 | 8·2 | 1·0 |
| Organic matter, CO ₂ , etc. | 67·7 | 77·3 | 84·6 | — | — |
| Total solids | 246·4 | 476·0 | 407·6 | — | — |

It will be observed that the total concentration of the Rothamsted drainage water varies from ·02 to ·05 per cent.

Organic Matter.

The distinguishing characteristic of soil is that it contains part of the complex material synthesised by plants. This material affords energy to numerous micro-organisms, and is gradually converted by them into simple substances appro-

¹ A. Voelcker's analyses of five samples collected between 1866 and 1869 (289).

² Von Seelhorst's analyses of samples collected weekly, or fortnightly, from a field between August, 1899, and August, 1900 (258).

priate for plant nutrition. We may look upon its constituents as taking part in a perpetual cycle: in one stage nourishing the growing plant and storing up the energy of sunlight, in the other stage nourishing micro-organisms and liberating energy. In addition, it has important physical effects on the soil. Unfortunately, not much is known of the highly complex components of the plant and even less is known about the important organic substances of the soil. The difficulty of working with insoluble, unstable bodies mingled with twenty times or more their weight of sand, silt, and clay has hitherto proved almost insuperable. The ideas current in the textbooks go back to the time before organic chemistry arose, and have come down direct from C. Sprengel (270*a*), Mulder (205) and Detmer (84).

We can thus only speak in the most general terms about what is admittedly the characteristic component of soil. Two great groups are to be carefully distinguished: one furnished by recent generations of plants; the other deposited with the soil during its formation, and therefore as old as the soil itself. Unfortunately, no actual method of separation is known, but some idea of the amount and properties of the original organic matter can be obtained from a study of the subsoil at depths below the root-range of plants. Ten feet or more below the surface, sandy subsoils usually contain less than .01 per cent. of nitrogen and clays less than .05 per cent., but shales contain more than 0.1 per cent. The percentage of carbon fluctuates, but is usually five to ten times that of nitrogen (200*a*). Now these values are about one-tenth to one-fifth of those obtained in the surface soil, so that at the very outside, and assuming there has been no decomposition, not more than 10 to 20 per cent. of the surface organic matter is original.

The organic matter furnished by recent vegetation may roughly be classified as: (1) material that has not yet had time to decompose and still retains its definite cell structure; (2) partially decomposed and still decomposing material; (3) simple soluble decomposition products; (4) plant or animal constituents not decomposable in the soil.

The undecomposed material is important as the reserve supply for the entire chain of reactions to be considered later. It also has a certain mechanical effect in opening up the soil and facilitating aeration and drainage, an effect useful on clays but often harmful on sands where these processes already tend to go too far.

The partially decomposed material forms a particularly vague and indefinite group containing all the non-volatile products of bacterial, fungal, enzymic and other actions on the plant residues. It shades off in one direction into the simple soluble decomposition products, and in the other into undecomposed plant fragments, so that it cannot be sharply defined or accurately estimated. A detailed study of the group being thus out of the question, we must ascertain in the first instance what part it plays in determining those relationships between the soil and the living plant that it is our business to study, and then, when we know what to look for, try to discover what constituents are important from our point of view and fix attention on them. For the preliminary inquiries recourse is had to the indirect method of correlation already used in ascertaining the properties of the mineral fractions of the soil. Numerous studies on these lines have proved that this group (or some component) possesses at least six properties not usually shown by the undecomposed plant residues.

1. It gives a dark brown or black colour to the soil.

2. It can withdraw various ions— NH_4 , K, PO_4 —from their solutions. The experiments of van Bemmelen (19, 21) indicate a complete parallelism with clay in this respect.

Baumann and Gully (10) and Odén (218*b*) show that undecomposed sphagnum can absorb ions from solutions, but the phenomena differ in detail from those shown by humus.

3. It causes the soil to puff up, or in the expressive phrase of the German farmer, to "ferment" (*Bodengärung*), and so leads to an increase in the pore space (see p. 220). From this results a marked improvement in the tilth and general mechanical condition. The Rothamsted mangold plots re-

ceiving no organic manure, and therefore poor in partially decomposed organic matter, get into so sticky and "unkindly" a state that the young plants have some difficulty

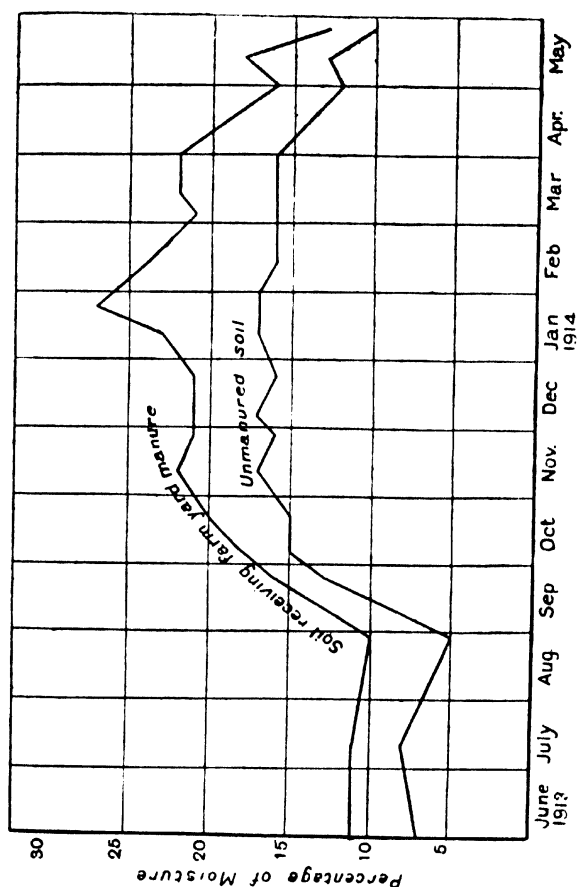


FIG. 17.—Curves showing the percentage of water in two soils on adjacent plots, one of which annually receives farmyard manure while the other does not. (Broadbalk field, Rothamsted.)

in surviving however much food is supplied, and may fail altogether if bad weather intervenes in the spring (as in 1908 and 1911); the dunged plots which are rich in this group are much more favourable to the plant and never fail to give

a crop. But the puffing up or "lightening" may go too far, and sometimes causes much trouble in old gardens that have long been heavily dunged.

4. It increases the water-holding capacity of the soil. The amounts of moisture present in adjacent plots at Rothamsted are shown in Fig. 17, from which it appears that the plot annually receiving farmyard manure contains normally 3 or 4 per cent. more water than the adjoining plot receiving no organic manure.

The variations in water content follow very closely the variation in the amount of organic matter present. So marked are these physical effects that if 15 or 20 per cent. of organic matter is present in a soil the operation of other factors ceases to count for much, and the distinctions between sands, loams, and clays are obliterated. Thus, much of the famous Red River prairie soil of Manitoba is identical in mineral composition with certain poor infertile Wealden soils, but the presence of 26 per cent. of organic matter completely masks the harmful effect of the clay and fine silt. A similar pair of soils, owing their difference in agricultural properties to their different organic matter content, have been analysed by C. T. Gimingham (106) (Table XXXVIII.).

TABLE XXXVIII.—EFFECT OF ORGANIC MATTER¹ ON THE TEXTURE OF SOILS.

| | Good Texture. | Poor Texture. | Good Texture. | Poor Texture. |
|--------------------|---------------------|---------------|--------------------------------|---------------|
| | Manitoban Prairies. | Weald Clay. | (Reported by C. T. Gimingham.) | |
| Fine gravel . . | — | 5 | — | — |
| Coarse sand . . | 1.6 | 1 to 2 | .6 | .5 |
| Fine sand . . | 3.8 | 10 ,, 12 | 4.3 | 8.4 |
| Silt . . | 17.1 | 20 ,, 30 | 11.2 | 13.8 |
| Fine silt . . | 28.2 | 25 ,, 30 | 28.7 | 26.5 |
| Clay . . | 23.3 | 20 ,, 25 | 23.8 | 25.0 |
| Loss on ignition . | 26.3 | 5 ,, 8 | 19.8 | 14.5 |

¹ Measured by the loss on ignition.

5. It swells when wetted.¹

6. Although the group is essentially transitional it has a certain degree of permanency and only slowly disappears from the soil. It disappears more rapidly from chalky and sandy soils than from loams and clays.

These properties greatly enhance the fertility of the soil, and in most schemes of husbandry definite arrangements are made to keep up or even increase the supply of organic matter, while in forests the removal of leaves and other decomposable material has led to such bad effects that in all state forests of France, Belgium, Germany, etc., the practice is absolutely forbidden.

The group of substances possessing these properties is generally called "humus," and so long as the word is used in a collective sense as a convenient label it may be retained. But the practice has been responsible for a good deal of loose thinking, because it obscures the fact that the group is an indefinite and complex mixture, and gives instead the impression that it is a single definite substance.

From these half-dozen general properties we may infer that humus is a brown, slowly oxidisable colloid. Careful examination of a number of soils in their vegetation relationships has shown that there must be several distinct types of humus but the laboratory methods are not yet as sensitive as the growing plant and fail to explain some of the differences observed by ecologists. We have to look to field observations for the facts on which to base a scheme of classification.

Peats.—Most of the recorded investigations are on peats

¹ Peat shows this phenomenon in a marked degree; indeed, after heavy rainfall inadequately-drained peat bogs may swell so much as to overflow into valleys with disastrous results. After drainage, however, drying and shrinkage set in, followed by a slow but steady erosion as air penetrates into the newly-formed spaces and starts the oxidation processes. When Whittlesey Mere was drained in 1851 a pillar was driven through the peat into the underlying gault, and the top of the pillar was made flush with the surface of the soil. So great has been the subsequent shrinkage that over 10 feet of the pillar is now out of the ground and the process has not yet reached its limit, for a perceptible shrinkage took place during the dry season of 1911.

of various kinds, and in this country the work has been done largely by Dr. Moss and other members of the British Vegetation Committee (279). At least three great classes and another two that may be transition forms were recognised:—

1. Dry peat (the German *Trockentorf*) found on heaths in relatively dry regions and on poor sandy soils. It is often only a fraction of an inch in thickness, and is largely formed by lichens and mosses (e.g. *Cladonia rangiferina*, *Polytrichum piliferum*, and others). The dominant plant is *Calluna*. Much of the organic matter of heath soils, however, often consists of undecomposed vegetation, e.g. bracken fronds, etc.

1a. In wetter districts the layer of peat becomes thicker, and no doubt changes in composition, but it still carries essentially "heath" vegetation, although it shows resemblances to 2.

2. Wet peat (the German *Hochmoor*) formed in wet tracts or regions of high rainfall, and accumulating to so great a depth that it entirely determines the character of the vegetation whatever the underlying rock. It receives no supplies of spring or underground water, and, therefore, no dissolved salts; the drainage water is acid and poor in soluble mineral matter. Two great divisions are recognised: *lowland moors* or mosses, formed in low-lying wet places largely from sphagnum, cotton grass (*Eriophorum*), and *Calluna*; and *upland moors*, formed mainly from *Eriophorum* spp. and *Scirpus cæspitosus* in elevated districts of high rainfall.

3. Fen (*Niedermoor* in German, see (299)) formed from a calcicolous vegetation (*Phragmites*, *Cladium*, *Scirpus*, *Carex*, etc.), in presence of calcium carbonate and soluble mineral salts, showing no acid properties and giving alkaline drainage waters.

3a. Carr, genetically related to the fen, containing much decaying tree residues, and formed in what at one time was a marshy wood.

Between fen and peat several transition forms have been described by Weber (299) and also recognised in England. Some of our moors are built up on older fens.

Forbes¹ recognises three classes of peat in Ireland :—

1. Mountain peat, corresponding with the wet peat low-land moss of the British Committee, which originates wherever the conditions are too sterile or the subsoil too impervious or water-logged to allow deep-rooted vegetation to flourish, and where, therefore, shallow rooted plants come in and, on dying, form a layer of organic matter on which sphagnum, cotton grass, etc., begin to develop. This occurs above the 800 feet level in most parts of Ireland, but in the west it often covers the entire surface down to the sea-level.

2. Marsh peat, corresponding with the British fen, which arises from reeds, sedges, rushes, etc., and which, so long as the water contains lime and nutrient salts, is as favourable a medium for plant growth as ordinary soil, though it affords no root-hold for trees, so that they are liable to be overturned in strong gales. This kind of peat forms the basis of all the low-land bogs in Ireland and of many of the small bogs in mountain districts.

3. This marsh peat finally becomes so consolidated with time and pressure that it loses connection with the water table, and a surface swamp forms on which a sphagnum bog of the "mountain type" arises. This, therefore, becomes similar in character to the first group: it differs, however, in its uniformity of growth, being higher in the centre than at the margins where soil water can get in and where, therefore, decomposition is more rapid.

The Scotch peats have been described by Lewis² and the Yorkshire moors by Elgee.³

Within each of the great classes described above several subdivisions are recognised, but how far they arise from differences in the organic matter, or from other differences, cannot yet be ascertained.

¹ A. C. Forbes, *Clare Island Survey*, 1914, 9 (*Proc. Roy. Irish Acad.*, 1914, 31).

² *Trans. Roy. Soc., Edinburgh*, 1905, 41, 699-724; 1906, 45, 335-360; 1907, 46, 33-70; 1911, 48, 793-833.

³ F. Elgee, *The Moorland of North-Eastern Yorkshire*. London, 1912.

Numerous chemical analyses of the peats have been made by Tacke at Bremen (278), Gully (116), Michelet and Sebelien (199) and others.¹

As a general rule, though with many exceptions, the percentage of nitrogen varies with that of the lime, and the high moor contains least of these, the low moor a larger quantity, and the fens a still larger quantity (Table XXXIX.).

TABLE XXXIX.—NITROGEN AND CALCIUM CONTENT OF VARIOUS PEATS.

| | | Nitrogen per cent. in Dry Matter. | CaO per cent. in Dry Matter. | Observer. |
|-----------|------------|---|------------------------------------|----------------------|
| High moor | Bremen | 1'14 | 0'44 | Tacke |
| | Lancashire | 0'85 | 0'11 | Russell and Prescott |
| Low moor | Bremen | 1'62 | 1'24 | Tacke |
| | Cheshire | 0'91 | 0'16 | Russell and Prescott |
| Fen | Norfolk | 2'85 | 7'5 | " " |

The investigations on the cause of the acid properties of peat are dealt with on p. 111.

Humus of Forest Soils.—An admirable series of studies has been made by P. E. Müller (206) of the types of humus occurring in the Danish forests.² In beech forests he found two types, which he called *mull* and *torf*, our nearest equivalents being mould and peat. On *mull* the characteristic plants were *Asperula odorata* with its associated *Mercurialis perennis*, *Milium effusum*, *Melica uniflora*, *Stellaria nemorum*, and others, moss being absent. The *mull* itself was only a few inches thick, and was underlain by 1 to 5 feet of loose soil, lighter in colour than *mull*, but almost equally rich in organic matter; still lower came a compact but porous layer of soil. The surface of the soil was covered by a layer of leaves, twigs, etc. Earthworms were numerous throughout; their potent influence in the soil had recently been shown by Darwin (76). Detailed chemical examination was not made: it was shown, however, that *mull* was free from acid and contained about 5 to 10 per

¹ See *Jahresber. Agrik. Chem.*, 1878, p. 29; 1904, pp. 87, 88, etc.

² Other investigations on forest humus are dealt with by Ramann, *Forstliche Bodenkunde u. Standortslchre*, 1893.

cent. of organic matter completely disintegrated and most intimately mingled with the mineral matter.

Torf differed completely. The characteristic plant was *Trientalis europæa* with the associated *Aira flexuosa* and moss, but surface vegetation was not very common. The loose layer of leaves was absent, and the *torf* itself was so tough and compact that rain water could not readily penetrate. Below it was a layer of loose, greyish sand (*bleisand*), and lower still a layer of reddish soil (*roterde*), or else a pan (*ortstein*). Practically no earthworms were found in the *torf*, but there were numerous moulds and fungi, *Cladosporium humifaciens* Rostrup and *Sorocybe Resinæ* Fr. being perhaps the commonest.

Torf was acid, contained about 30 per cent. of organic matter not completely disintegrated, nor well mixed with the mineral matter. It was not very favourable to the growth of young trees, and the forest tended to become an open heath as the old trees died.

The distribution of *mull* and *torf* did not seem to be determined by the nature of the soil, or by the amounts of soluble alkali salts or calcium carbonate present, but rather by the nature of the living organisms in the soil. Animals, especially earthworms, gave rise to *mull*, fungi produced *torf*. If the conditions were favourable to earthworms *mull* was therefore found, if not, *torf* was produced. The nature of the vegetation was also a factor: oak only rarely formed *torf* but commonly gave rise to *mull*, at least two varieties of which were observed; pine, like beech, could form either *torf* or *mull*, while *Calluna vulgaris* and *Vaccinium myrtillus* generally produced *torf*.

Humus of Field Soils.—It is commonly assumed that the humus of field soils is of the same nature as that of peat, fen, or forest. There are undoubtedly certain properties in common. Alway and Neller (3*d*) find that the differences in moisture content of adjacent plots of varying organic matter content can be explained on the assumption that soil organic matter has the same water-holding capacity as the most absorbent peats, *i.e.* three to four times its own weight. The difference in organic matter was 1·37 per cent.; the difference in moisture

was up to 4 per cent. A close study jointly by a botanist and a chemist would carry the problem much nearer to a solution.

The observations indicate that the mixture we have agreed to call humus does not vary erratically from field to field, but produces much the same effects over any tract where similar soil and climatic conditions prevail. The mixture changes when a new set of conditions occurs, but its general character persists over a certain range and then it merges into another type. Two great divisions of the types can already be recognised: a neutral group commonly spoken of as neutral humus or "mild humus," and a group reacting like an acid and called "sour humus," acid humus, or by German writers *Rohhumus*.

TABLE XL.—ANALYSES OF THE ORGANIC MATERIAL EXTRACTED BY ALKALIS FROM SOIL (OFTEN CALLED HUMUS, SOLUBLE HUMUS, ACTIVE HUMUS, *MATIERE NOIRE*, ETC.).

| Source. | Carbon. | Hydrogen. | Oxygen. | Nitrogen. | Ash. | Observer. |
|--|---------|-----------|---------|-----------|-----------------------------|--|
| Arable land . . . | 56.3 | 4.4 | 36.0 | 3.3 | Cal- culated ash-free | Mulder (205) |
| Garden soil . . . | 56.8 | 4.9 | 34.8 | 3.5 | | " |
| Pasture land . . . | 56.1 | 5.3 | 32.5 | 6.1 | | " |
| Peat . . . | 59.0 | 4.7 | 32.7 | 3.6 | | " |
| " . . . | 57.4 | 4.6 | — | <1 | — | F. Fuchs ¹ |
| Rich prairie soil . . | 45.1 | 3.7 | 28.6 | 10.4 | 12.2 | Snyder (268) |
| Soil never cultivated | 44.1 | 6.0 | 35.2 | 8.1 | 6.6 | " |
| Cultivated subsoil (a) | 48.2 | 5.4 | 33.2 | 9.1 | 4.2 | " |
| " (b) | 50.1 | 4.8 | 33.7 | 6.5 | 4.9 | " |
| "Humic acid" from sugar . . . | 66.4 | 4.6 | 29.0 | — | — | Berthelot and André (30-32) |
| "Humic acid" from compost . . . | 53.3 | 5.6 | 37.5 | 3.6 | — | Berthelot and André (30-32) |
| "Humic acid" from sugar through K salt . . . | 64.70 | 4.55 | 30.71 | — | — | Robertson, Irvine and Dobson ² |
| "Humic acid" from sugar through NH ₄ salt . . . | 64.74 | 4.69 | 29.81 | 0.76 | — | Robertson, Irvine and Dobson ² |
| "Humic acid" from soil through K salt | 56.67 | 5.16 | 35.68 | 2.49 | — | Robertson, Irvine and Dobson ² |
| "Humic acid" from soil through NH ₄ salt . . . | 54.29 | 4.94 | 38.16 | 2.61 | — | Robertson, Irvine and Dobson ² |

¹ *Chem. Zeit.*, 1920, 44, 551. The molecular weight was about 680.

² *Biochemical Journ.*, 1907, 2, 458. For other studies see Mary Cunningham and Chas. Dorée, *Trans. Chem. Soc.*, 1917, III, 589-608.

In order to understand much of the chemical work that has been done, it is necessary to remember that the older chemists regarded humus as a single definite substance, or as a mixture of two or three definite substances. The favourite view was to consider neutral humus as the calcium salt of "humic acid," which could be extracted from the soil by dilute alkalis after preliminary treatment with hydrochloric acid. On acidifying this alkaline extract the "humic acid" came down as a brown colloidal precipitate. Acid humus was the actual humic acid itself. It was further supposed that humic acid could be synthesised by boiling sugar with hydrochloric acid, on the singularly inadequate ground that the product thus obtained is also a brown colloid, soluble in alkalis and precipitated by acids. Numerous analyses have been made both of the natural and the synthetic "humic acid," some of which are given in Table XL.¹

Robertson, Irvine, and Dobson give the formula $C_{39}H_{32}O_{14}$ to humus from sugar and $C_{24}H_{24}O_{11}N$ to the soil humus obtained through the potassium salt; the latter may be related to the acid prepared from Dopplerite by Mayer,² containing

¹ Many partial analyses have been made. Cameron and Breazeale (654) in nineteen samples obtained percentages of carbon varying from 33.3 to 50.1, whilst Hilgard (133b) found the nitrogen content to be:—

| | Percentage of Humic Acid in the Soil. | Percentage of Nitrogen in the Humic Acid. |
|---|---------------------------------------|---|
| Soils of the arid regions (decomposition rapid) | 0.20 to 3.0 | 8.7 to 22.0 (average 15.2) |
| Soil of the sub-irrigated arid regions | 0.36 " 2.0 | 5.4 " 10.8 (" 8.4) |
| Soil of the humid regions (decomposition slow) | 1.0 " 10.0 | 1.7 " 7.0 (" 4.2) |

C. B. Lipman, however, is convinced that there is an error here: he has not found more than 7 or 8 per cent. of N in the humus from arid soils: this is no more than occurs in the humus from humid soils (*Soil Science*, 1916, 1, 285-290). He also finds no difference in general nitrifying power (*Journ. Ag. Research*, 1916, 7, 47). Westermann (302) has analysed humus from the Danish moors, and Gully (116) has studied humus from South Bavarian moors. Many of the older analyses have been collected by Wollny (318).

² *Landw. Versuchs*, 1883, 29, 313.

58.2 per cent. carbon and 5.0 per cent. hydrogen. In view, however, of Hoppe-Seyler's discovery, confirmed by Odén,¹ that soil humus is partly soluble and partly insoluble in hot alcohol, it is obvious that at least two substances must have been present in the material analysed in the above cases and the validity of any formula becomes doubtful.²

The purification of humus for investigation in the laboratory is rendered extraordinarily difficult by its colloidal nature, which was demonstrated by van Bemmelen in a remarkable paper in 1888 (19). Baumann's researches (10) have carried the subject a good deal farther, and it is now known that "humus," freshly precipitated by acids from an alkaline extract of soil, compost, etc., possesses the following colloidal properties :—

- (1) Very high capacity for retaining water.
- (2) Extraordinary shrinkage on drying.
- (3) Is coagulated by acids and salts, the electric current and frost.
- (4) Reversibility, *i.e.* the freshly precipitated material redissolves when the precipitant is washed away.
- (5) Decomposes salts—calcium carbonate, calcium phosphate, etc.
- (6) Forms difficultly soluble and easily decomposable colloidal mixtures with other colloids.
- (7) Masks certain ion reactions (*e.g.* Fe cannot be detected by potassium ferrocyanide, etc.).
- (8) Forms absorption compounds.

The colloidal nature of the humus accounts for much of the failure of the earlier chemical work, and it adds to the difficulties of those modern chemists who have had the courage to tackle the problem. In spite of these difficulties several good investigations have been made.

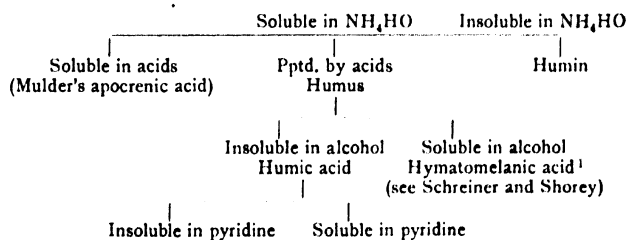
¹ *Ber.*, 1912, 45, 651.

² Miklaur (*Zeit. f. Moorkultur u. Torfverwertung*, 1908, 285) and Mayer both showed that variations in the time or the method of extraction cause differences in the results even from the same soil. Sostegni (*Landw. Versuchs-Stat.*, 1886, 32, 9) had shown that humus is readily fractionated.

Schreiner and Shorey (250) have attempted a resolution of the "humic acid" and of the "crenic acid" (the part not precipitated by HCl) and have obtained the following substances from the alkaline or alcoholic extract:—

| Substances Precipitated by Acids (the so-called Humic and Ulmic Acids). | Substances not Precipitated by Acids (the so-called Crenic and Apocrenic Acids). |
|---|--|
| <i>Resin acids.</i> <i>Resin esters.</i> <i>Glycerides.</i> <i>Paraffinic acid</i> , $C_{24}H_{48}O_2$, m.pt. 45° - 48° , probably identical with the acid formed on treating paraffin with fuming nitric acid. <i>Lignoceric acid</i> , $C_{24}H_{48}O_2$, m.pt. 80° - 81° , isomeric with above. <i>Agroceric acid</i> , $C_{21}H_{42}O_2$, m.pt. 72° - 73° , a hydroxy fatty acid. <i>Agrosterol</i> , $C_{26}H_{44}O$, m.pt. 237° . <i>Phytosterol</i> , $C_{26}H_{44}O \cdot H_2O$, m.pt. 135° . Both of the cholesterol group. | <i>Dihydroxystearic acid</i> , $C_{18}H_{36}O_4$, m.pt. 98° - 99° , identical with the acid formed on oxidising elaidic acid <i>α-Picoline γ-carboxylic acid</i> , $C_7H_7O_3N$, m.pt. 239° , identical with the acid formed on heating uvitonic acid to 274° . <i>Xanthine</i> , $C_5H_4O_3N_4$. <i>Hypoxanthine</i> , $C_5H_6ON_4$. <i>Cytosine</i> , $C_4H_5ON_3 \cdot H_2O$. <i>Histidine</i> , $C_6H_7O_2N_3$. <i>Arginine</i> , $C_6H_{14}O_2N_4$. <i>A pentosan</i> . |

None of these, however, is the black substance which is the real characteristic of "humus," and until recently this had eluded investigation and was vaguely described as a "melanoid body". It can be split up by solvents into the following substances which are no doubt further resolvable:—



The substances are probably related: at any rate they occur together. There is good evidence that soil humus is formed mainly from cellulose: no great amount is produced from protein. Addition to the soil of wool, silk waste, flour, and lucerne meal causes no gain, but on the contrary loss of

¹ For Hoppe-Seyler's hymatomelanic and fulvic acids see Odén, 219c.

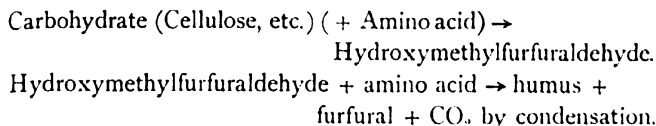
humus.¹ This formation from cellulose suggests an interesting possibility as to its origin. It has already been stated that a substance resembling humus is formed on heating sugar with hydrochloric acid (*e.g.* 250 grms. dextrose with 1 litre 24 per cent. HCl for 12 hours). Maillard has shown (189*b*) that the reaction is general and not confined to strong acids.

He was led by his investigations on the function of alcohol in the synthesis of albuminoids to study the action of a typical amino acid, glycocoll, on d-glucose. When 1 part of glycocoll and 4 parts of glucose were added to 3 to 4 parts of water and heated on the water-bath to facilitate dissolution the reaction mixture rapidly changed to yellow and finally to dark brown, CO₂ being given off. The action was a true condensation and not an oxidation, for practically no oxygen was absorbed. The black material had the properties of soil humus: it was insoluble in water, dissolved in alkalis, but was reprecipitated on adding acids, and contained 4.4 to 6 per cent. nitrogen: this question is discussed at length in the later paper (189*d*). The reaction turned out to be general, and was given by all the amino acids tried (glycocoll, sarcosine, alanine, valine, leucine, tyrosine, glutamic acid and also the polypeptides) and all the sugars. Xylose and arabinose reacted especially quickly, fructose, galactose, glucose, and mannose less quickly, and lactose and maltose still less, while saccharose acted only slowly. The reaction proceeds at ordinary temperatures, but more slowly.

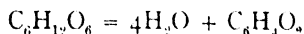
Now it is certain that both amino acids and pentose compounds are formed during the decompositions in the soil, the former from the proteins and the latter from the celluloses, and it is highly probable that the black substance is formed by their interaction. A detailed study of the reaction was therefore made at Rothamsted by V. A. Beckley (12); setting out from an observation by Fenton, he showed that sugars, on treatment with acids, give rise to hydroxymethylfurfuraldehyde, which readily condenses to form a substance closely re-

¹ Gortner, *Soil Sci.*, 1917, 3, 1-8.

sembling humus. He also found indications of hydroxymethylfurfuraldehyde in a dunged soil and in rotting straw in which humus was being produced. He suggests, therefore, that the formation of humus in the soil proceeds in two stages :—



Eller and Koch,¹ on the other hand, suppose that humus is formed by the oxidation of quinones which arise by the elimination of water from hexoses :—



Beijerinck (17) has already found quinone among the products of certain soil organisms working in culture solution.

As to the constitution of humus little is known. Sven Odén of Upsala (218*a*) has adduced evidence from the conductivity of the solution in ammonia that the alcohol insoluble portion is a true acid, as was supposed by the older chemists and by Tacke (278). Ehrenberg and Bahr (93*d*) also agree with this view : they show that it neutralises sodium hydroxide, the point of neutralisation being sharply indicated by conductivity measurements. On dilution the sodium compound behaves as a salt or a tri- or tetra-basic acid. Further evidence of true acidic nature is afforded by the fact that the alkaline solution behaves as a true solution, and shows none of the properties of colloids (Odén, 218*b*). There is, however, another view (see p. 111) that the acidic properties are the result of the colloidal condition and not of a true acid constitution, but it is improbable that this is a complete explanation of the phenomena.

For a long time the humus soluble in alkalis was supposed to play a great part in determining fertility: Grandeau (112*a*) and Hilgard (133) especially considered it to be the most

¹ Wilhelm Eller and Käte Koch, *Ber.*, 1920, 53 B, 1469-1476.

useful material for making plant food. Methods for determining its amount in soils were elaborated and many estimations were made. But nothing came of them: on the Rothamsted plots about one-half of the total nitrogen is soluble and one-half insoluble in alkalis whatever the manurial treatment. The idea rested on no experimental basis and, in the only recorded tests, Weir (300*a*) found that the removal of this soluble nitrogen caused no diminution in the productivity of the soil. If this turned out to be general it would show that the really important nitrogen reserves are in the insoluble part, as is not unlikely in view of the circumstance that they probably consist of protein and similar bodies which do not dissolve in alkalis.

An indirectly beneficial effect on the plant is suggested by Briggs, Jensen, and McLane's observations that the percentage of mottling in citrus trees of S. California is inversely related to the amount of soluble humus in the soil: they therefore recommend mulching with straw so that the decomposition products can be washed into the soil.¹

Kaserer² suggests that an important function of humus in the soil, so far as micro-organisms are concerned, is to act as a carrier of the numerous inorganic constituents they require.

Wax-like Constituents.

Some of the soil organic matter is wax-like in properties, interfering very much with the wetting of the soil and the movement of the water. As it decomposes only slowly it tends to accumulate in rich soils and to become rather troublesome. It can be extracted by organic solvents, *e.g.* toluene, and obtained as a yellowish-brown mass containing appreciable quantities of nitrogen (a soil yielded .003 per cent. of a substance containing 3 per cent. of nitrogen in one of the writer's analyses).

¹ *Journ. Ag. Research*, 1916, 6, 721; and 1917, 9, 253.

² H. Kaserer, *Internat. Mitt. f. Bodenkunde*, 1911, 1, 367-75.

The Nitrogen Compounds in the Soil.

It is convenient to collect together the main *data* connected with the nitrogen compounds of the soil. The total nitrogen in arable soils is usually about 0.15 per cent., in pasture soils

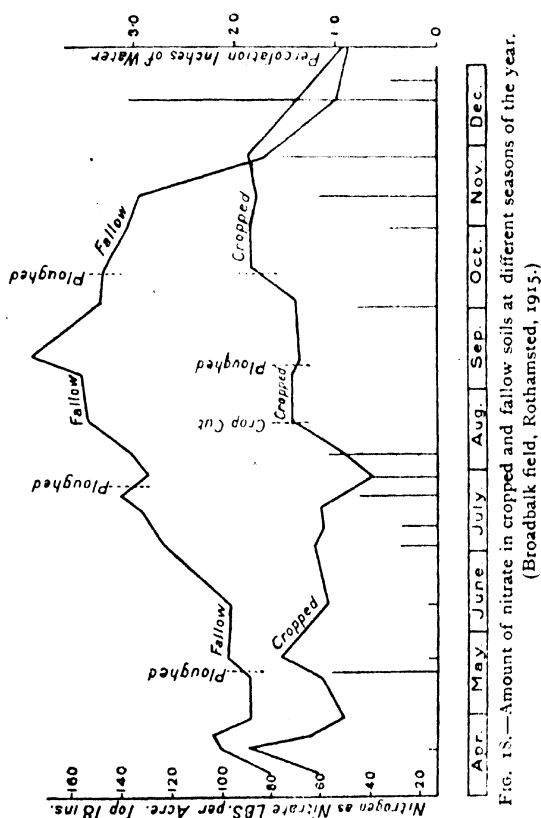


FIG. 13.—Amount of nitrate in cropped and fallow soils at different seasons of the year. (Broadbalk field, Rothamsted, 1915.)

about 0.3 per cent.; higher amounts are present in chalk soils and still higher in fen, moorland, and black prairie soils. About half of the nitrogen in arable soils is contained in compounds soluble in alkalis, and a small proportion in unstable compounds readily breaking down to ammonia. The

amount of nitrogen present as free or combined ammonia is about '0001 per cent. (i.e. 1 part per 1,000,000) in arable soils not rich in organic matter,¹ and some ten times this quantity in pasture or heavily dunged arable soils; much larger quantities occasionally occur in special cases, as in heated soil, but abnormal growth effects are then produced.² There is considerable variation in the amount of nitrogen present as nitrate; rich garden soils may contain 60 or more parts per 1,000,000 ('006 per cent.), arable soils 2 to 20 parts ('0002 to '002 per cent.), pasture soils rather less and woodland soils still less.³ No soil constituent fluctuates more in amount than nitrates; plants and rain rapidly remove them and bacterial action rapidly forms them. The producing agencies are active in spring, and work throughout summer and autumn, while the removal agencies are active in summer and winter. Thus the amount of nitrate actually present in arable soil is usually highest in spring, falls in summer, often rises somewhat in autumn, and falls again in winter as shown in Fig. 18 (p. 145) (see also Table LXVI., p. 249).⁴

The nitrate and ammonia together rarely account for more than 1 per cent. of the nitrogen in the soil: the remainder is in more complex forms. The part soluble in alkalis⁵ probably includes the same type of compound as was obtained by Maillard in the condensation of sugars and amino acids (p. 142). The part insoluble in alkalis may be of protein nature. On boiling with strong HCl soluble nitrogen compounds are formed, and it has been supposed⁶ that the reaction qualitatively and quantitatively resembles protein hydrolysis. This may be true, but exact proof is difficult.

¹ André (*Compt. Rend.*, 1903, 136, 820) obtained higher results in early spring which he attributed to the cessation of nitrification, but not of ammonification, during winter.

² See E. J. Russell and F. R. Petherbridge, *Journ. Ag. Sci.*, 1913, 5, 248.

³ It is sometimes stated that woodland soils do not contain nitrates and are, unsuited for nitrification, but Weis (301) has shown this to be incorrect.

⁴ For American data see R. Stewart and J. E. Greaves, *Centr. Bakt. Par.*, 1917, 34, 115.

⁵ After preliminary treatment with dilute acid (see p. 139).

⁶ E.g. Jodidi, *Iowa Research Bull.*, No. 1, 1911.

Morrow¹ has shown that the figures for the distribution of nitrogen given by the van Slyke method are unreliable in presence of ferric chloride, which always occurs in soil extracts. Potter and Snyder have studied the amino-nitrogen in soil.²

¹ *Soil Sci.*, 1918, 5, 163.

² *Journ. Amer. Chem. Soc.*, 1915, 37, 2219, and *Journ. Ag. Res.*, 1916, 6, 61.

CHAPTER IV.

THE COLLOIDAL PROPERTIES OF SOIL.

GRAHAM in 1861 introduced the term "colloids," to denote those bodies which, like glue, tend to form jellies rather than crystals, and which possess certain properties distinguishing them from crystalloids, such as high power of absorbing water and also dissolved substances from their solution. The idea subsequently arose that colloids were a distinct group of bodies, and when clay was observed to possess colloidal properties chemists went to much trouble to try and isolate the colloidal constituent: Schloesing (245*b*) described a process that required several weeks for its performance. Later on, however, it was recognised that colloids are not a group of substances but a state into which most solid substances can be brought: their properties are attributed to their highly extended surface. Any substance, therefore, that can be brought into a sufficiently finely divided state, or can be got into a "web" structure so as to make its surface sufficiently large, will show colloidal properties.

Van Bemmelen was the first to show how completely the clay and humus in the soil behave like colloids. And, as both these substances dominate the soil to a considerable extent, it is not remarkable that the soil as a whole possesses colloidal properties.

It is not my purpose to write a chapter on the properties of colloids. The soil student must, however, make himself thoroughly familiar with them¹ because he will find at every

¹ Convenient accounts of the properties of colloids are given by Hatschek in *An Introduction to the Physics and Chemistry of Colloids*, London, 1913; by Wo. Ostwald, in *Colloid Chemistry*, translated by Fischer, London, 1916; and by R. Zsigmondy, *Chemistry of Colloids*, translated by E. B. Spear, New York, 1917. For a good discussion see W. D. Bancroft, *Journ. Phys. Chem.*, 1914, 18, 552; and 1916, 20, 85.

turn that the colloidal nature of the soil modifies or even determines its behaviour and leads to all sorts of unexpected results.

So far as the soil is concerned the most striking colloidal properties are :—

(1) The power of absorbing substances from their solutions.

The absorption is in effect a precipitation: it may be regarded as a concentration of the absorbed body on the surface of the colloid and in this sense it is called an "adsorption". It differs from a simple chemical precipitation in that it does not follow the ordinary laws of chemical reaction but special laws of its own. In general, but not invariably, the adsorption by colloids can be expressed by the equation $\frac{y}{m} = Kc^p$ where

c = the concentration of the dissolved substance when equilibrium is attained;

y = the amount absorbed by a quantity m of the adsorbent;

(this can readily be expressed as $(a - c)$ where a = the initial concentration);

K and p = constants depending on the nature of the solution and adsorbent.

As we shall see, this equation fits a large number of soil reactions.

(2) The power of absorbing water in considerable amount and holding it rather loosely: parting with it again by evaporation in a continuous manner without any critical points or regions.

(3) The change that can be brought about in some of the finer mineral particles from the flocculated to the deflocculated state, and *vice versa*. This is particularly shown by clay and has been discussed on p. 105.

(4) The property whereby some of the soil components can enter into solution in pure water (not, however, a true solution) and be thrown out again on addition of small

quantities of electrolytes. The former state is called a "sol," the latter a "gel".

The effect of these properties has not yet been fully studied. It will, therefore, be most convenient to deal with a few directions in which work has been done, and this plan will have the double advantage of showing how the new ideas have developed and how far reaching is likely to be their effect in soil chemistry.

Absorption by Soil.¹

The facts of absorption by soil have long been known: they were established, indeed, by the end of the sixties. Soluble salts, such as ammonium or potassium sulphate, which might be expected to wash out of the soil with rain, do not, as a matter of fact, do so, but are kept back in such form that the plant can get them. In becoming absorbed, however, these substances displace something else, and conversely they can themselves be displaced by another salt. Hence there arise a series of interchanges which profoundly affect the nutrition of the plant.

The first quantitative investigation was made by Thompson (282) who showed that ammonium sulphate is decomposed when dissolved and shaken with soil, ammonia being fixed and calcium going into solution. The problem was taken up by Way (298) who found that the quantities of ammonia absorbed and of calcium displaced were equivalent. Further experiments by A. Voelcker (289*a* and *b*) and others, showed that the same action takes place in the soil itself when ammonium sulphate is added in the ordinary way as manure, an insoluble nitrogen compound being formed which remains in the soil, while the calcium sulphate washes out in the drainage water. Potassium sulphate reacts in the same way, the potassium being precipitated and an equivalent amount of calcium going into solution. Potassium phosphate undergoes a more

¹ The literature of this subject has been summarised by J. A. Prescott in *Journ. Ag. Sci.*, 1916, 8, 111-130.

complete precipitation, since calcium phosphate is insoluble. The precipitated potassium compound dissolves somewhat in water, but it has no definite solution pressure, instead the amount of potassium dissolving increases with the amount present. It can also be decomposed by sodium salts; hence addition of sodium sulphate to the soil increases the amount of soluble potassium ions and to this extent acts like a dressing of potassic manure. Magnesium salts have a similar effect, and, like sodium salts, lead to an increase in the amount of potassium available for the crop. Some of Lawes and Gilbert's results (166*a*) are given in Table XLI.

TABLE XLI.—EFFECT OF SODIUM AND MAGNESIUM SULPHATES IN INCREASING THE SUPPLY OF POTASH TO THE PLANT. LAWES AND GILBERT (166*a*).

| | Ammonium Salts only. | Ammonium Salts + Super- phosphate. | Ammonium Salts + Super- + Sulphate of Sodium. | Ammonium Salts + Super- Sulphate of Magnesium. | Ammonium Salts + Super- + Sulphate of Potassium. | Ammonium Salts + Super- Sulphate of Sodium, Magnesium, and Potassium. |
|--|-------------------------|--|--|---|---|--|
| 1852-1861. | Plot 10. | Plot 11. | Plot 12. | Plot 14. | Plot 13. | Plot 7. |
| K ₂ O in ash of straw, per cent. | 18·8 | 14·8 | 10·1 | 22·0 | 24·1 | 23·7 |
| K ₂ O in ash of grain, per cent. | 33·9 | 31·7 | 32·8 | 32·6 | 32·9 | 32·9 |
| Weight of K ₂ O in ten whole crops, lb. | 300 | 309 | 454 | 498 | 532 | 560 |
| 1862-1871. | | | | | | |
| K ₂ O in ash of straw, per cent. | 14·5 | 14·1 | 17·2 | 18·5 | 25·0 | 24·6 |
| K ₂ O in ash of grain, per cent. | 34·1 | 32·1 | 33·3 | 33·1 | 33·5 | 33·4 |
| Weight of K ₂ O in ten whole crops, lb. | 240 | 260 | 378 | 391 | 552 | 530 |
| Total amount of K ₂ O taken by crop dur- ing the twenty years, lb. | 540 | 569 | 832 | 889 | 1084 | 1090 |

In the twenty years the sodium sulphate has enabled the plant to take up an additional 263 lb. of K₂O, whilst the

magnesium sulphate has furnished it with an extra 320 lb. over and above what the crop on Plot 11 can get.

On the other hand, gypsum has no such effect. The superphosphate applied to Plot 11 contains a considerable proportion of calcium sulphate, but it does not increase the weight of potassium in the crop. This appears to be the general rule: Briggs and Breazeale¹ obtained the same result on Californian soils. The result is at variance with a statement commonly made that potassium is dissolved out when soil is shaken with calcium sulphate solution.²

Some ions are not precipitated in the soil, including CO_3 , SO_4 , NO_3 , Cl , Mg , Ca , Na ; ³ these are, therefore, the chief constituents of drainage water (see p. 128).

Organic substances, particularly those of high molecular weight, are also withdrawn from their solutions, but the reaction is apparently of a different type, since nothing appears to be given up from the soil in exchange. The result is of extreme importance; practically the whole of the organic matter added to the soil by plant residues or manure remains near the surface unless carried down mechanically by some agency such as earthworms. Even when heavy dressings of dung are annually supplied at Rothamsted there is after fifty years no appreciable enrichment of the subsoil in nitrogen (Table XLII.). The purification of sewage by land treatment affords further illustrations of the absorptive power of soil for organic matter. In English experience a sewage farm on a good loam can deal with 30,000 to 40,000 gallons of sewage per acre per day (*i.e.* 1·3 to 1·8 inches per day).

¹ *Journ. Ag. Res.*, 1917, 8, 21.

² *E.g.* Hilgard, *Soils*, 1906, p. 43; probably based on experiments by E. Heiden, *Jahresber. Agrik. Chem.*, 1868, p. 59; *Annal. Landw. Preussen.*, 1868, 50, 29; Kalmann and Bocker, *Landw. Versuchs-Stat.*, 1878, 21, 349. See also G. André, *Compt. Rend.*, 1913, 157, 856.

³ From the time of Aristotle it has been known that sea water could be "desalted" by filtering through sand or soil. But it has been shown by Von Lipman and Erdmann (*Chem. Zeit.*, 1911, xxxv., 629) that the water first running through the sand filter is not desalted sea water, but displaced water. When this has all gone the salt water runs through unchanged.

TABLE XLII.—NITROGEN IN BROADBALK WHEAT SOILS, 1893.

Per cent of dry soil.

| | Annual Dressing of Manure. | | | | | |
|------------------|----------------------------|-------------------------|-------------------|---|---|--|
| | Unmanured. | Dung (200 lb. N). | Minerals only. | Minerals + 200 lb. Ammonium Salts (43 lb. N). | Minerals + 400 lb. Ammonium Salts (86 lb. N). | Minerals + 600 lb. Ammonium Salts (129 lb. N). |
| Top 9 in. . . | '0992 | '2207 | '1013 | '1107 | '1222 | '1188 |
| 9 to 18 in. . . | '0730 | '0767 | '0739 | '0720 | '0681 | '0752 |
| 18 to 27 in. . . | '0651 | '0656 | '0645 | '0628 | '0583 | '0630 |

Lb. per acre.

| | | | | | | |
|---|------|--------|------|------|------|------|
| Top 9 in. . . | 2572 | 5150 | 2630 | 2870 | 3170 | 3080 |
| 9 to 18 in. . . | 1950 | 2050 | 1970 | 1920 | 1820 | 2010 |
| 18 to 27 in. . . | 1820 | 1830 | 1800 | 1750 | 1630 | 1760 |
| Nitrogen supplied in manure in the 50 years . | None | 10,000 | None | 2150 | 4300 | 6450 |

The Mechanism of Absorption.—In a classical investigation Way (298a) argued that the absorption is purely chemical: the ammonia and the calcium simply changed places as usual in double decompositions or precipitations. He then proceeded to discover the particular constituent of the soil with which the reaction took place; he found it was neither the calcium carbonate, the sand, the undecomposed rock, however finely ground, nor the organic matter.¹ The active constituent was in the clay, but it formed only part of the clay, and, moreover, it lost its power on ignition. No known simple silicates showed these properties, but he prepared a number of "double silicates" of lime and alumina, of soda and alumina, etc., that did; thus they reacted, like clay, with ammonium salts to

¹ It was subsequently shown by König (153) that soil organic matter has a marked power of absorbing ammonia from ammonium sulphate.

form an almost insoluble double ammonium silicate and a soluble calcium salt, and also, like clay, they lost this property after ignition. Although he did not establish the existence of such double silicates in soil, their resemblance to the reactive constituent in the soil was so close that he considered himself justified in assuming their presence.

This chemical view was generally accepted in England, but it was controverted by Liebig, who held that the whole phenomenon was physical and comparable with absorption by charcoal. Plant food constituents occur in the soil in two states: chemically combined and physically retained: the latter being the looser is the more suited for the purposes of plant nutrition. "The power of the soil to nourish cultivated plants," he writes, "is therefore in exact proportion to the quantity of nutritive substances which it contains in a state of physical saturation. The quantity of other elements in a state of chemical combination distributed through the ground is also highly important, as serving to restore the state of saturation, when the nutritive substances in physical combination have been withdrawn from the soil by a series of crops reaped from it" (174*d*, pp. 67-69).

Knop (150) combined both chemical and physical hypotheses. The absorption of acid radicles he attributed to precipitation by the iron and aluminium hydroxides supposed to be present in soil: phosphoric acid, however, reacted first with the calcium compounds to form calcium phosphate and then with the iron compounds. With bases the action was rather more complex: the absorption in the first instance was due to a surface attraction, which was followed by a combination with silica or aluminium silicates: there was, however, invariably an equilibrium, the whole of the base never being removed, no matter how dilute the solution.

Liebig's proposition which we have quoted above was expressed more tersely by Knop as follows: Soils of great fertility have a high content of easily replaceable bases; and he measured this by determining the ammonia absorbed from a 0.5 per cent. solution of ammonium chloride, assuming that,

as absorption was only a substitution, the greater the amount of replaceable base the greater would be the absorption of ammonia. The method was applied to a number of soils and gave results in fair agreement with their agricultural history. It was somewhat modified by Kellner,¹ who measured the quantities of potassium and calcium displaced and found that they agreed exactly with the amounts taken up by plants in pot culture. The method was still further improved by Ramann: a 5 per cent. solution of ammonium nitrate is allowed to percolate through the soil and the displaced potassium and calcium are estimated.² A detailed study has been made by Prianischnikow (229a).

Van Bemmelen (20a) began by accepting Way's chemical hypothesis, and showed that soils with a high power of absorption usually contained a large quantity of easily decomposable silicates (19a): Way's double silicates would presumably be of this nature. Further, absorption of bases always involved displacement of other bases from the soil, a strong indication of chemical change. Later on, however, he made extensive studies of absorption by simple gels: silica, alumina, ferric hydroxide, tin hydroxide, etc., and found it closely to resemble absorption by soils: other studies of colloids were made and in each case the similarity to soil phenomena was so close as to leave no doubt that soil was essentially a colloid and soil absorption simply a manifestation of the colloidal properties.

This new idea was soon found to explain many of the old discrepancies. Chemists had several times attempted to bring the phenomena of absorption equilibrium into line with those of chemical equilibrium, but the equations would not fit except for a narrow range of concentrations. Boedecker in 1859³ had fitted an expression to Henneberg and Stohmann's results for ammonia absorbed and calcium displaced in the interaction

¹ O. Kellner, *Landw. Versuchs-Stat.*, 1886, **33**, 349.

² Recorded by J. A. Hanley in *Nature*, 1914, **93**, 59%. See also Kullenberg, *Jahresber. Agric. Chem.*, 1865, **8**, 15.

³ *Journ. f. Landw.*, 1859, 48.

between soil and ammonium sulphate, and Hall and Gimingham (120*e*), dealing with the same reaction, showed that the ordinary formula for chemical equilibrium held over a limited range of concentrations; but Cameron and Patten (65*b*, see also 300) found that it did not hold over a wider range. The absorption of potassium could not be fitted at all by the formula.

When, however, the adsorption formula is used a complete fit can be obtained: Wiegner (308) has gone over the recorded data and shown that they all fit the equation given on page 149, *viz.*,

$$\frac{y}{m} = Kc^{\frac{1}{p}},$$

the constants having the values given in Table XLIII. The constants vary with changes in experimental conditions, and they are by no means absolute quantities. But for a given set of conditions they remain unchanged.

TABLE XLIII.—VALUE OF "CONSTANTS" OBTAINED IN ADSORPTIONS BY SOIL. WIEGNER (308).

| Absorbent. | Solute. | K. | $\frac{1}{p}$. | Worker. |
|-----------------------------|--------------------|--------|-----------------|--------------------------|
| Garden soil | NH ₄ Cl | 0.0948 | 0.039 | } Henneberg and Stohmann |
| " " | NH ₄ Cl | 0.131 | 0.424 | |
| Nile sediment . . . | NH ₄ Cl | 0.489 | 0.399 | } Armsby |
| Permutite | NH ₄ Cl | 2.823 | 0.398 | |
| Sodium zeolite } artificial | CaCl ₂ | 2.487 | 0.317 | } Armsby |
| Zeolite | LiCl | 24.419 | 0.414 | |
| Soil | NH ₄ OH | 0.0994 | 0.434 | } Brustlein |
| " | NH ₄ OH | 0.147 | 0.461 | |
| " | NH ₄ OH | 0.054 | 0.386 | |

We still, however, have to account for the fact that the absorbed bases displace an equivalent amount of some other bases from the soil—a procedure which would be wholly unnecessary if nothing but adsorption were involved. This is done by supposing that only the hydroxide is absorbed: the acid radicle in general is not: it therefore dissolves out some of the bases from the soil. As this is a purely chemical re-

action the amount of base brought out is equivalent to the acid set free, *i.e.* to the amount of base adsorbed by the soil.

Thus the modern position is essentially that of Knop, but the idea has been expanded, and, above all, the phenomena have been connected up with a wide range of others.

Miyake's experiments (202*a*) indicate that the rate of absorption of the ammonium ion by soil follows the ordinary time rate for the diffusion of liquids into absorbing substances, *viz.* $x = Kt^m$ where x = the amount absorbed, t = time and K and m are constants. The rate, however, is affected by the presence of other ions.

The absorption of potassium by soil has been studied by Schreiner and Failyer,¹ by Patten and Waggamann² and recently by McCall, Hildebrandt and Johnston.³

The Action of Dilute Acids on Soils.

It will be shown later that the reaction between dilute acids and soil is of very great importance to the soil chemist in enabling him to form some estimate of the amounts of the mineral plant nutrients present. The reaction ought in principle to be simple, but numerous investigations by Hall and Amos (120*a*), de Sigmund and others, have shown that it is not, and that it falls quite out of line with the ordinary chemical reactions. In particular different acids, even at equivalent concentrations, do not dissolve out the same amount of material, nor can any connection be traced between the "strength" of the acid and the amount of its action.

Russell and Prescott (241*b*) have studied the reaction between dilute acids and the phosphates in the soil and find that it can be interpreted as a simple solvent action followed by an adsorption.

When a soil is acted upon by a dilute acid the amount of P_2O_5 dissolved is found to increase continuously with the concentration of the acid. The curves obtained for different

¹ Bull. 32, U.S. Bureau of Soils, 1906.

² Bull. 52, U.S. Bureau of Soils, 1908.

³ Journ. Phys. Chem., 1916, 20, 51-63.

acids are all of the same type, but they show two remarkable peculiarities: (1) some of the strong acids, such as hydrochloric and nitric, bring out less P_2O_5 than the weaker citric and oxalic acids at equivalent concentration; (2) the amount of action is not always proportional to the time, and in the case of some acids, *e.g.* hydrochloric and nitric, there is actually less P_2O_5 dissolved after 24 hours' action than after 20 minutes (Fig. 19).

Amount of P_2O_5 extracted from soil by HNO_3 of varying concentration acting for different times.

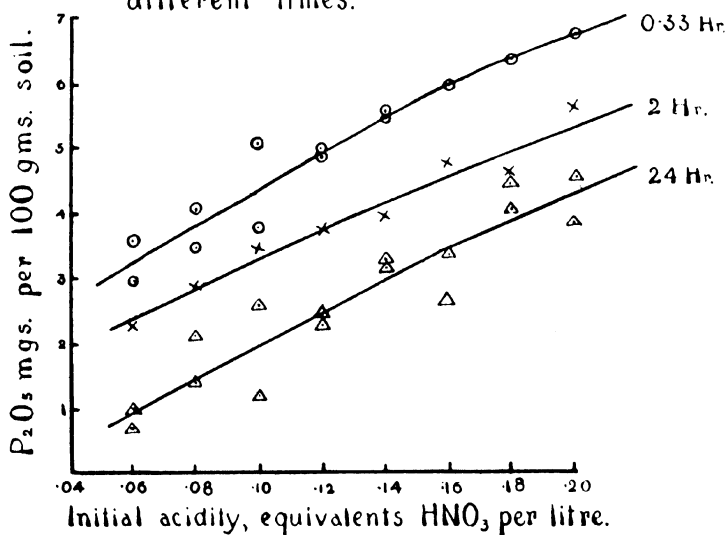


FIG. 19.—Amount of P_2O_5 extracted from soil by HNO_3 of varying concentration acting for different times.

This second result indicates that a reverse action is coming into play, proceeding more slowly than the direct action: so that after 20 minutes the effect is determined largely by the direct action, while after 24 hours it is determined by the reverse action.

The reverse action was eliminated by a diffusion method. When this was done all dilute acids were found to act in a very

similar manner and the peculiarities disappeared. The direct action of dilute acids on soil phosphates, therefore, appears to be a simple chemical reaction of the ordinary kind.

The reverse action was investigated by swamping the direct action by adding sodium phosphate to the solution: it was

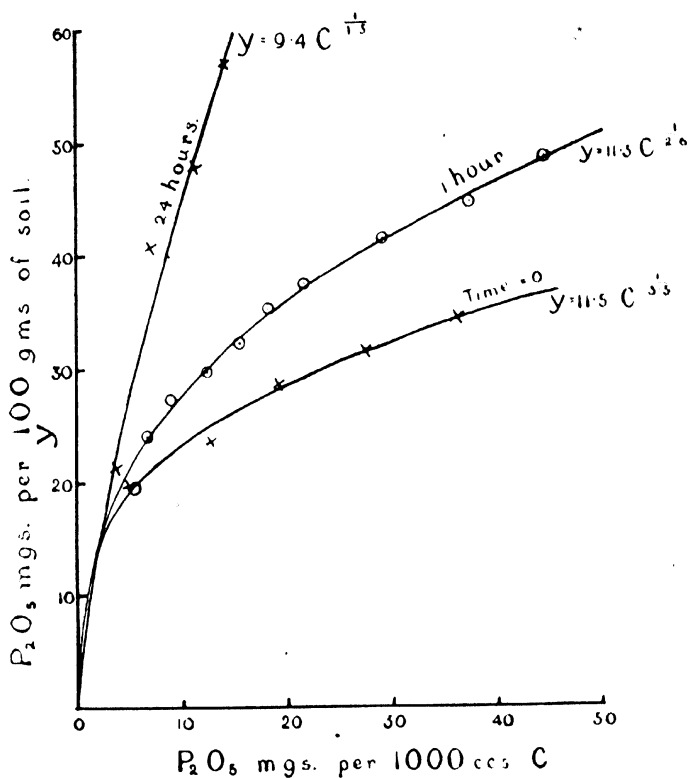


FIG. 20.—Showing that the experimental points obtained in the action of dilute acid on soils lie on adsorption curves.

found that P_2O_5 was absorbed from the solution notwithstanding the presence of acid, and the phenomenon was of the ordinary type fitted by the equation given on page 149. Absorption was not confined to phosphoric acid: it also

occurred with oxalic acid and citric acids but not with hydrochloric and nitric acids.

Thus the reaction of the soil phosphorus compounds with dilute acids may be resolved into two separate actions: a direct action of the acid on the phosphorus compound, and an adsorption of the dissolved P_2O_5 by the soil. In high acid concentrations the former action predominates, but both actions always go on. The solvent action is practically the same for nitric, hydrochloric, and citric acids of equivalent strengths, and appears to be the normal action of an acid on a phosphate. The reverse action, the adsorption, can be expressed by the equation which has been found to fit so many others. It is considerably influenced by the acid being greater in the presence of the mineral acids than of the organic acids. The amount of phosphorus compound actually brought out is the difference between the direct and the reverse action. Thus hydrochloric acid dissolves out a certain amount of phosphate, but considerable adsorption takes place, so that the net amount left in solution becomes small. Citric acid dissolves out the same amount of phosphate, but there is much less adsorption, and therefore the amount left in solution is markedly greater. The difference between the various dilute acids lies, therefore, not so much in their solvent power, which is very similar for all, but in their influence on the adsorption process.

Flocculation of Clay and Silt.

It is customary to divide colloids in a state of suspension in a liquid into two groups according as they do or do not combine with the liquid; those which do not combine but may be supposed to possess a surface sharply separating them from the medium are often called suspensoids, while those that do combine and possess no sharp surface of separation are called emulsoids. This nomenclature is not always used, even the distinction is not universally recognised, and is probably not always valid, but it covers a good many cases.¹

¹ E.g. it is not accepted by R. Zsigmondy, *Chemistry of Colloids*, translated by E. B. Spear, 1917, p. 27.

As a rule the suspensoids are readily precipitated by traces of electrolytes; emulsoids, on the other hand, are not, but usually require salting out. The phenomena have been explained by W. B. Hardy (122) on an electrical hypothesis and by Freundlich as the result of selective adsorption of the coagulating ion.¹

Hardy (122, p. 238) supposes that the particles of suspensoids remain suspended so long as they carry an electric charge, *i.e.* so long as there is a difference in electric potential between them and the liquid in which they are immersed. But they precipitate immediately this charge is neutralised by an opposite charge, or to be more precise, as soon as they attain the same potential as the liquid. This point where the difference in electric potential has disappeared is called the isoelectric point.

The flocculation of clay has been much investigated. Schloesing in 1870 (245*d*) discovered the main facts and demonstrated the reversibility of the process. References to subsequent work will be found in Wolkoff's paper.² The general result is that clay behaves like an electro-negative colloid; it is deposited at the anode on the passage of an electric current through its suspension,³ and it is flocculated by positively charged ions, but beyond a certain point it is deflocculated or rendered still more disperse by negatively charged hydroxyl ions. The flocculating effect depends more on the valency than the atomic weight of the cation; univalent cations are less effective than bivalent, which in turn are less effective than trivalent ions;⁴ there is, however, no simple proportionality between valency and flocculation (Hall and Morison, 120*d*). In some cases, if not all, some absorption of the flocculating ions occurs and the phenomena are therefore more

¹ For a discussion of these views see W. C. McC. Lewis, *A System of Physical Chemistry*, Vol. I., p. 362 (Longmans).

² *Soil Sci.*, 1916, 1, 585-601.

³ Advantage is taken of this property to purify clay from admixed coarser grains of silica. The process is known as electro-osmosis.

⁴ Among recent papers see Leoncini (172); Wo. Ostwald, *Kolloid Zeitsch.*, 1920, 26, 69-81; N. Bach, *J. Chim. Phys.*, 1920, 18, 46-64.

nearly expressible by an absorption curve.¹ Pickering (226a) has demonstrated an absorption in the case of clay.

Comber (69) has observed an interesting difference in the flocculation of silt and of clay. Silt behaves like other suspensions of particles insoluble in water; it is flocculated by small quantities of electrolytes, and the flocculation proceeds most rapidly at the iso-electric point. Flocculation is hindered by the presence of hydroxyl ions which increase the negative charge, and therefore calcium nitrate is a more potent flocculator than lime. This is the normal behaviour of such suspensions under the conditions of the experiment.

Clay, on the other hand, behaves differently; flocculation by small quantities of electrolytes is most rapid in slightly alkaline solutions, away from the iso-electric point. Lime is a better flocculator than calcium nitrate. In order to account for the difference Comber assumes that the clay particles are coated or protected with a layer of emulsoid silica which impresses emulsoid characters on the whole system. On this view the OH ion "peptises" the protecting emulsoid and the Ca ion then flocculates the clay. Support for this view was found in the fact that addition of colloidal silica to a ferric oxide suspension made the system behave like clay, flocculated more easily in alkaline than in neutral solutions.

These observations throw important light on the well-known difference between clay and silt² (p. 107).

Odén discusses the protective effect of humic acid on the coagulation of clay.³

Pan Formation.

A pan is a layer of hard impermeable rock that gradually forms at the usual water level below the surface of the soil under certain conditions. Its effect is to cut off the soil above from the material below and therefore to modify profoundly

¹ Linder and Picton, *Trans. Chem. Soc.*, 1895, **67**, 63. For further work see H. Freundlich, *Zeit. f. phys. chemie*, 1910, **73**, 385-423.

² See also Otto M. Smith, *J. Amer. Chem. Soc.*, 1920, **42**, 460-472.

³ Sven Odén, *J. Landw.*, 1919, **67**, 177-208.

the movements of water and of air, leading often to swamp conditions. The effect on vegetation becomes so marked that in agricultural practice the pan has usually to be removed, often at considerable trouble and expense.

The conditions determining the formation of pan seem to be a supply of organic matter, permeability of soil, low content of soluble mineral matter, and absence of calcium carbonate. These conditions occur most frequently on light sandy soils where for some reason the water is held sufficiently near the surface.

Pans are best seen when the sand is overlain by a deposit of peat. The sand is then bleached to a depth of 5 to 60 cms. Suddenly there comes a change: a coloured layer of solid rock occurs which may vary in colour from yellow to black and in thickness from 10 to 60 cms.: on closer inspection this is seen to consist of particles of sand cemented firmly together. This is the pan:¹ underneath it lies the sand proper. But pans are by no means confined to peat: they often occur in forests, on heaths and on certain cultivated soils.

Chemical analysis shows that the pan is much richer in organic matter, iron, alumina, and especially material displaceable by ammonium nitrate solution than either the sand above or the sand below. Table XLIV. gives typical results showing the amounts of material soluble in HCl.

The process of pan formation, therefore, involves a concentration of these substances in a certain layer of the soil.

On the older view humic acid was supposed to be formed from the organic matter present, and to dissolve iron, alumina, and other substances, forming soluble humates which were washed down into the soil and precipitated at the point where pan formation occurred.

Various hypothesis were advanced to account for these changes.

¹ In German the pan is called "Ortstein" and the bleached sand "Bleisand," "Bleichsand," or occasionally "Grausand". When the formation, instead of being sand, is clay, the white soils are called "Molkenböden". Some of these are described in *Internat. Mitt. Bodenkunde*, 1914, 4, 105-137. See also (24).

TABLE XLIV.—ANALYSES SHOWING CONCENTRATION OF IRON, ALUMINA, AND ORGANIC MATTER IN THE PAN.

| | Pan from Caesar's Camp (Morison and Sothers) (204). | | | Pan from Freudenstadt, Black Forest (Münst). | | |
|--|--|------|-----------------------|---|-------|-----------------------|
| | Bleached Sand. | Pan. | Soil below Pan. | Bleached Sand. | Pan. | Soil below Pan. |
| Hygroscopic moisture | 1'27 | 3'06 | '90 | '300 | 3'79 | '768 |
| Loss on ignition | 1'84 | 7'22 | 1'36 | — | — | — |
| Material soluble in NH_4NO_3 | — | — | — | 1'577 | 10'92 | 1'946 |
| Fe_2O_3 | { | '493 | 4'066 | { | '253 | 1'857 |
| Al_2O_3 | | | | | | |
| CaO | | | | | | |
| MgO | | | | | | |
| K_2O | | | | | | |
| Na_2O | { | '080 | '350 | { | '180 | 4'946 |
| P_2O_5 | | | | | | |
| SiO_2 | | | | | | |
| | | | | | | |
| | | | | | | |
| | trace | '037 | '018 | trace | '019 | '021 |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | — | '084 | '110 | — | '015 | '118 |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | — | '087 | '155 | — | '035 | '172 |
| | | | | | | |
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| | | | | | | |
| | | | | | | |
| | — | — | — | — | '011 | '041 |
| | | | | | | |
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| | | | | | | |
| | | | | | | |
| | — | — | — | — | '029 | '059 |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | — | — | — | — | '312 | 2'698 |
| | | | | | | |
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| | | | | | | |
| | | | | | | |

Mayer (194), extending the earlier work of Emeis,¹ supposed that anærobic conditions arose during part of the year when the land was waterlogged, and humic acid was then formed and the iron reduced to the ferrous state. Ferrous humate is soluble in water and therefore washes downwards: even aluminium silicate becomes partly soluble. At a certain depth this ceases; various causes may come into play: the water table may be reached, or there may be an accumulation of washed-down clay on which the humates are precipitated. Then in the dry part of the year oxygen can gain access to this depth, converting the ferrous humate to ferric humate, which being insoluble is protected against further washing.

Ramann modified this somewhat by assuming that precipitation occurred when the solution of iron humate reached the zone, intermediate between the surface soil and the sub-soil, where he supposes weathering to be still proceeding and where, therefore, there is a larger proportion than usual of soluble reactive mineral salts.

As an alternative Hall suggested that the solvent is CO_2 : the iron is reduced to the ferrous state by the organic matter

C. Emeis, *Waldbauliche Forschungen und Betrachtungen*, Berlin, 1875.

and is then dissolved as ferrous bicarbonate. At the lower level the CO_2 escapes and the iron carbonate is precipitated and then oxidised.

These explanations seem very simple but they present several difficulties. In the first place, Morison and Sothers could find no evidence that peat or humic acid can reduce ferric oxide, the first stage in the process, according to Mayer. Ferric chloride is easily reduced: so easily, indeed, that ferrous iron is produced during the process of testing a mixture of ferric oxide and peat if one begins by extracting with HCl ; but ferric oxide is not. Secondly, it is difficult to understand why the deposition should be so local and so sharply defined.

Recent workers, therefore (Münst,¹ Ramann,² Morison, and Sothers (204), regard the whole process as a formation first of a "sol" and then of a "gel," and Morison and Sothers suggest the following as the most probable course of events.

It is well known that "sols" change to "gels" in presence of small quantities of electrolytes, and conversely "gels" often change to "sols" when electrolytes are removed. In normal soils the conditions are favourable to gel formation, but when in these particular soils the upper layer of sand becomes denuded of its soluble material by the persistent washing of rain water, the conditions become favourable for the formation of sols of ferric hydroxide and of humus—or ferric humate, if one likes to put it that way. Morison and Sothers actually obtained such sols³ by persistent washing of ferric-humus gels.

As the sol is washed down some is deposited on the bleached sand, but the bulk of it passes to the permanent water level where it remains and accumulates, diffusion being practically non-existent. During the dry months a certain amount of desiccation takes place, involving a deposition of the sol as a gel: there is also a certain amount of transformation

¹ Münst, *Bied. Zentr. Agrik. Chem.*, 1912, 41, 3-10.

² Ramann, *Bodenkunde*, Berlin, 1911, p. 204. See also H. Stremme, *Kolloid Zeitsch.*, 1917, 20, 161-168.

³ As might be expected these did not give the ordinary iron reactions.

of sol to gel through the presence of electrolytes in the ground water.¹ Some of the humus gel becomes oxidised, some of both humus and ferric gels change their colloidal properties in other ways. When wet weather comes on again it is no longer possible for the whole of the deposited gel to change back to a sol: some will no doubt change, and there will be a certain washing down of the gel deposited on the bleached sand. But where the bulk had accumulated deposition has begun, and the place where this happened serves as a seat of further action.

This view seems more in accordance with the facts than the older one and it does not involve any unproved assumptions—such as reduction of ferric to ferrous iron and presence of ferrous iron in the pan.

There is another type of pan formation which must not be confused with this. On clay soils the continued ploughing to a uniform depth with heavy ploughs often leads to the consolidation of the underlying soil and the formation of a compact layer of clay or ploughsole which behaves like rock. This effect is purely physical, it can be overcome by periodically sending a subsoiler behind the plough to break through the mass.

The Retention of Water by Soil and the Rate of Evaporation.

The older chemists and physicists divided the soil moisture into two kinds: free water, which was supposed to be suspended on the particles just as sea water is suspended on grains of sand or as oil on leaden bullets; and hygroscopic water, which was retained in a closer sort of way so that it could not be taken up by plants or micro-organisms. Methods for discriminating between these were devised, and pot experiments were made to ascertain directly the amount of free water available for the plant.

The first experiments made on the rate of evaporation of water from soil gave broken curves which could be explained

¹ Ramann lays stress on this; Morison and Sothers do not, because their sols were very stable in presence of electrolytes.

on the assumption that these two kinds of soil water existed. Shull's results (see p. 224) presented more difficulty and led him to regard the state of the soil moisture as unbroken and continuous. Keen (146*a*) furnished rigid proof: he found that the relationship of water to soil differed fundamentally from its relationship to sand. The evaporation of water from sand, silt, china clay, and ignited soil proved to be relatively simple and could be explained by the known laws of evaporation and diffusion. But the evaporation of water from soil could not: it was more complex. Instead of the simple proportionality between water content and rate of evaporation observed in the case of sand, the curves for soil were more exponential in type. The difference was traced to the soil colloids and it disappeared when the soil was ignited and the colloidal properties lost: the curve then became identical with that obtained for sand. The influence of the colloids has so far only been expressed empirically, but it is probably connected with the relation between vapour pressure and moisture content. But there is clearly something else at work, for the curve is not of a simple exponential type. It is necessary to allow for another factor: the effect on the rate of evaporation of the decreasing water surface in the soil, the surface obviously diminishing in area as evaporation continues.

The equation finally developed by Keen is:—

$$A \frac{dw}{dt} = \left(\sqrt[3]{\frac{ws}{100}} + 1 \right) [2.303 \log_{10}(w + K) - \log_e K],$$

where $\frac{dw}{dt}$ = rate of evaporation.

w = percentage of water present by weight.

s = specific gravity of the soil.

A and K = constants.

This relationship holds without any break, proving that the water in a normally moist soil is all held in the same way without any break in physical state (Fig. 21). At one end of the curve the water is more easily given up than at the other, and in the competition for water between soil colloids and

plants or micro-organisms some kind of equilibrium may be attained under definite conditions: this equilibrium is the "wilting-point" of the physiologist. On this view the other constants and critical points that have been indicated by various investigators are all equilibrium points and do not represent breaks in the condition of water in the soil. Further discussion will be found on p. 218.

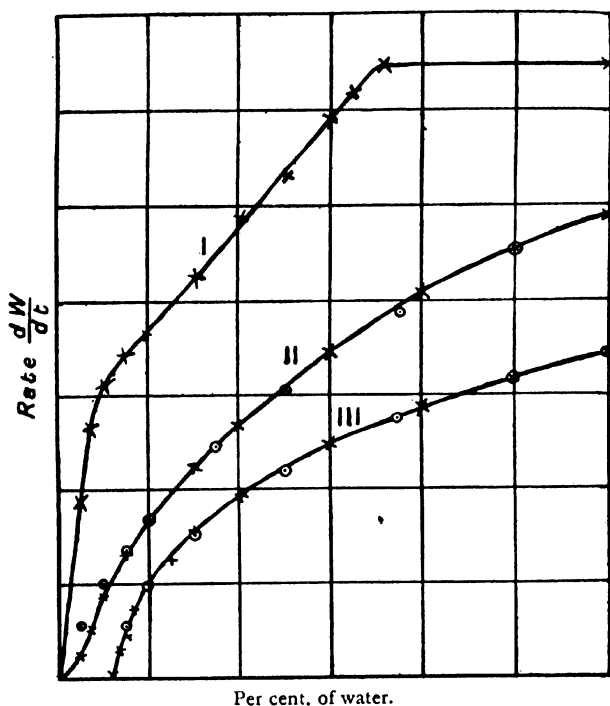


FIG. 21.—Curves showing rate of evaporation of water from: I. Ignited garden soil over conc. H_2SO_4 ; II. Arable soil (Hoos field, dunged) over conc. H_2SO_4 ; III. Arable soil (Hoos field, dunged) over 55.4 per cent. H_2SO_4 .

The Influence of Colloids on the Reactions Taking Place in the Soil.

It is obvious that a reaction taking place in a colloidal medium possessing properties like selective adsorption must

differ from one going on in aqueous solution such as most chemists are accustomed to think about. We must therefore be prepared for unexpected results: it is possible that some of the changes formerly attributed to bacteria may in part be due to colloids (see p. 215).

Further, the colloids influence both micro-organisms and plants (p. 239) and therefore indirectly affect the reactions in the soil.

Again, the remarkable changes observed in heated soils¹ and soils stored in a dry condition, such as the increase in amount of soluble matter,² in the rate of nitrification,³ and in the productiveness, are probably much influenced by changes in colloids.⁴ Gedroiz's⁵ experiments with oats grown in soils kept dry for a number of years are given in Table XLV.

TABLE XLV.—EFFECT OF STORAGE IN A DRY STATE ON THE PRODUCTIVENESS OF SOILS. (Oats: Gedroiz, 1908.)

| No. of Years of Storage. | No Manure. | Complete Manure. | Complete without Nitrogen. | Manure without Phosphate. |
|--------------------------|------------|------------------|----------------------------|---------------------------|
| 0 | 10.3 | 83.5 | 13.5 | 11 |
| 1 | 17.8 | 83.9 | 32.3 | 19 |
| 3 | 24.6 | 90.9 | 23.6 | 35.4 |
| 5 | 25.0 | 102.8 | 32.2 | 42 |

The Estimation of Soil Colloids.

Efforts have been made to determine the amount of colloidal material in the soil by studying the absorption of dye-stuffs or of water vapour. So far the results are not easy to interpret nor are they always related to the other colloidal phenomena. It would therefore be premature to attempt any

¹ S. U. Pickering, *Journ. Agric. Sci.*, 1910, 3, 32 and 254.

² U.S. Department of Agric. Bureau of Soils Bull. 8, p. 13; Bull. 22, p. 41; also *Journ. Agric. Res.*, 1918, 12, 383.

³ Buddin, *Journ. Agric. Sci.*, 1914, 6, 452-455.

⁴ For study of the biological changes in soil during storage see F. E. Allison, *Soil Sci.*, 1917, 3, 37, and W. Giltner and H. V. Langworthy, *Journ. Ag. Res.*, 1916, 5, 927.

⁵ Gedroiz, *Bull. Internat. Instit. Agric. Rome*, 1915, p. 37.

summary as yet: the student wishing full information may be referred to the papers on the absorption of dye-stuffs by Sjollem, ¹ Endell, ² Ashley, ³ König, Hasenbäumer and Hassler, ⁴ Hanley, ⁵ and Tadokoro, ⁶ the last-named giving other references also, and to Mitscherlich's papers on the absorption of water vapour. ⁷ The general discussion of Leeden and Schneider ⁸ may also be consulted.

The Constitution of the Soil.

The components of the soil do not form a mere casual mixture. A much more intimate mingling prevails, amounting almost to a loose state of combination, from which the separate substances are only extracted by drastic mechanical means, or gentle chemical treatment. The soil colloids and the calcium carbonate appear to be responsible for the formation of the compound particles, and as soon as they are altered by treatment, first with acid and then with alkali, the particles fall to pieces and the silt, clay, etc., can be readily separated by sedimentation processes. No method has been devised for measuring the size of the compound particles. Their existence can be shown in a clay soil by making two analyses of the same soil, one after the usual treatment with acid and alkali to break up the compound particles completely, the other on the untreated soil where the breaking up is only partial. The demonstration, however, does not work so well for loams (Table XLVI.).

The existence of these compound particles puts out of the question any complete quantitative interpretation of a mechanical analysis. The properties of a soil are not the sum of the properties of the separate fractions—clay, fine silt, etc.—be-

¹ *Journ. f. Landw.*, 1905, 53, 67.

² *Kolloid Zeitsch.*, 1909, 4, 246.

³ H. E. Ashley, *The Colloidal Matter of Clay and its Measurement* (U.S. Geol. Sur. Bull., 388, 1909).

⁴ *Landw. Versuchs-Stat.*, 1911, 75, 377.

⁵ J. A. Hanley, *Journ. Agric. Sci.*, 1914, 6, 58.

⁶ T. Tadokoro, *Journ. Tohoku Imp. Univ. Sapporo* (Japan), 1914, 6, 27.

⁷ These are summarised in *Internat. Mitt. f. Bodenkunde*, 1912, 1, 463-480.

⁸ *Ibid.*, 2, 81.

cause in a normal soil these fractions, which we may regard as the ultimate particles, are largely bound together into compound particles. How far the properties of the ultimate particles are modified by this union we cannot say, but no very profound alteration seems to take place in the sands and silts because the properties of the separate fractions, deduced by correlation methods from studies of numerous soils, agree tolerably well with the properties revealed by direct experiments on the fractions themselves. The finer particles are more changed, the result being to minimise the effects of their smallness. Thus, while the limits within which the properties of a soil fall are determined by the ultimate particles, a considerable variation is possible within these limits through the formation of compound particles.

TABLE XLVI.—EFFECT OF COMPLETE DISINTEGRATION OF SOIL BY ACID AND ALKALI ON THE RESULTS OF MECHANICAL ANALYSIS OF A CLAY AND A LOAM.

| | Clay Soil, Woburn. | | Loam, Rothamsted. | |
|-------------------|--------------------------|----------------------------|--------------------------|----------------------------|
| | Disintegration Complete. | Disintegration Incomplete. | Disintegration Complete. | Disintegration Incomplete. |
| Fine gravel . . . | ·3 | ·2 | 1·3 | 1·3 |
| Coarse sand . . . | 8·3 | 8·6 | 9·5 | 8·5 |
| Fine sand . . . | 3·2 | 2·9 | 22·7 | 26·9 |
| Silt . . . | 8·6 | 12·1 | 32·3 | 33·6 |
| Fine Silt . . . | 11·2 | 13·3 | 8·9 | 9·3 |
| Clay . . . | 43·2 | 36·3 | 12·9 | 11·1 |

It is unfortunate that so little is known about the compound particles, because they play a great part in determining the relationships between soil and plant growth. They can be disintegrated by various cultivation methods, such as ploughing the soil when wet, or by allowing the stock of organic matter and calcium carbonate to fall too low, and when this has happened the "clay" properties become emphasised, so that the soil loses its fine crumbly state and is very apt to become sticky when wet, and to dry into a hard cake through which young plants can only force their way with difficulty.

The compound particles can be reformed by careful cultivation and by adequate additions of organic matter and calcium carbonate, but the process may take years, and it cannot be hastened until it is better understood.

In the preceding pages we have shown how many of the important soil properties are due to colloids. The formation of these compound particles, the absorption of soluble manures, the retention of water (in part), the swelling of the soil when wet and its shrinkage when dry, are all colloidal phenomena. If we regard the mineral particles as the skeleton of the soil we must look upon the colloids as clothing it in many of its essential attributes. How the colloids are arranged in the soil is not known, but the simplest view, and one in accordance with all the facts, is that the mineral particles, especially the fine silicate particles, are coated¹ with a colloidal complex containing silica, alumina, ferric oxide, alkaline bases, and phosphoric acid derived from the weathering of the rock material and the so-called humus. These various components are not in true chemical combination, but in a state of absorption, or solid solution. The complex is decomposable by changes in temperature, concentration of the soil solution, etc., but it decomposes continuously and not in the *per saltem* manner of ordinary chemical reactions. It can interact with various solutions, absorbing certain substances as a whole—*e.g.* organic dye-stuffs—or simply giving up to the solution an amount of base equivalent to what it has absorbed.

A wholly different conception of the constitution of the soil has been put forward by Whitney of the Bureau of Soils, United States Department of Agriculture, Washington (304-6). Soil particles are supposed to arise by disintegration and to consist of the original minerals of which the rock was composed; little importance is attached to the weathered silicates that play so large a part in the view just set out. Colloidal properties and the special clay properties begin to appear when the disintegration has gone so far that the particles become very minute: these properties are not associated with any par-

¹ See also 89a and b.

ticular complex, but are supposed to be exhibited by any substance that is sufficiently finely divided. Most agricultural soils arise from the same minerals and are therefore of similar chemical constitution: in consequence, the solution in contact with the particles, *i.e.* the soil moisture, is of similar composition and concentration for all soils. It is further supposed that, under similar climatic conditions, the concentration of any particular ion in the soil solution is not materially altered by addition of soluble salts, any such addition only forcing out of the solution a number of the ions already there. Special importance is attached to this soil solution and it is regarded as the food of plants¹ and the source of fertility of the soil; indeed, the function of the mineral part of the soil is mainly to hold up and distribute this solution. Soluble fertilisers, like potassium salts, are not supposed to increase the amount of food available to the plant, but to owe their beneficial effects to indirect actions in the soil, such as the precipitation of toxic substances, facilitation of movements of soil water, etc.

Controversy has arisen in three directions. It was at first supposed that the physical properties of the soil moisture were in the main deducible from the hypothesis that the water was suspended as on grains of sand or like oil on bullets (see p. 166). This has been shown to be inadequate; it is necessary to take the soil colloids into account.

The view that the soil solution is unalterable in composition led to considerable discussion. Hall, Brencley, and Underwood (121*d*) and F. H. King (147*b*) obtained diametrically opposite results to those of Whitney and Cameron.² It is now generally recognised that the composition of the soil moisture varies with the soil and the treatment, and, indeed, that the changes in composition are on the whole related to the fertility of the soil (see p. 125). Bouyoucos (49*c*) finds

¹ It is interesting to note that a controversy on this point was going on sixty years ago when agricultural chemists first began to use water cultures. See Schumacher, *Landw. Versuchs-Stat.*, 1863, v., 270-307.

² For bibliography of this discussion see Stewart, *Journ. Ag. Res.*, 1918, 12, 311-368.

that the addition of soluble salts other than phosphates increases the concentration of the soil solution. Much discussion has also arisen in regard to the supposed toxins: that is dealt with on p. 244.

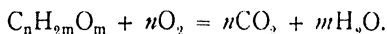
As developed more recently by Cameron (65c), however, the views of the American Soil Bureau have more in common with those of the British workers. The solid particles of the soil are supposed to consist of disintegrated rock minerals, along with adsorption complexes, solid solutions such as the so-called basic phosphates, and indeterminate substances in an extremely fine state of division apparently containing "humus," oxides of iron and aluminium, etc. The solubility of these constituents in water is influenced by three circumstances: their fine state of division, the presence of CO_2 in the soil water, and the fact that, as regards the solid solutions and adsorption complexes, some sort of distribution coefficient comes into play. Since the soil minerals are salts of strong bases with weak and almost insoluble acids they become more or less completely hydrolysed in solution, so that the concentration of the base would have to be very high before equilibrium was attained. It is therefore improbable in humid areas that equilibrium ever is attained. Moreover, and this is a central part of the thesis, soil phenomena are dynamic and not static; the soil moisture, the soil solution, even the very particles of the soil itself are in continual motion and state of change. Hence the composition of the soil solution must be continually changing.

But it is considered that the amount of change in composition is small in comparison with the changes in the soil, and such changes are not correlated with changes in the productiveness of the soil. All the factors in soil fertility are interdependent, and it is a mistake to confine attention exclusively to any one aspect of their action. Thus fertilisers should not be regarded exclusively as plant foods: they affect more or less every soil factor influencing crop production, and the problem can be satisfactorily solved only by discovering the nature and extent of these interrelations.

CHAPTER V.

THE CARBON AND NITROGEN CYCLES IN THE SOIL.

THE organic matter added to the soil by plants, etc., rapidly undergoes a number of changes in presence of air. Oxygen is slowly but continuously absorbed, and an almost equal volume of carbon dioxide is evolved, indicating that the main change is of the type—



Thus the carbon in the soil tends to fall off relatively to the nitrogen, and the ratio $\frac{C}{N}$ which, in the original plant material, e.g. the stubble, is about 40,¹ becomes reduced in the soil to 10 (Table XLVII.). Other products are formed as well, including ammonia and the dark-coloured humus bodies already described, but the details of these changes are unknown. Investigations with the individual plant constituents, cellulose, fats, various organic acids, proteins, have so far brought out little beyond the fact that they all oxidise to CO_2 in the soil, while the calcium salts of organic acids change to $CaCO_3$.

The absorption of oxygen by soil was demonstrated by de Saussure about 1800, studied by Boussingault (48), and definitely attributed by Schloesing to micro-organisms in 1883.² Wollny developed this thesis in 1884 (317) and showed that the rate of oxidation is much diminished by

¹ For leguminous crops, however, it is about 25.

² *Leçons de chimie Agricole*, 1883, p. 277: "C'était là, pensait on alors, un fait purement chimique. On sait aujourd'hui que c'est principalement un fait biologique, c'est-à-dire que la combustion observée est le résultat de la vie de nombreux organismes, tel par exemple que le ferment nitrique, lequel est chargé de transporter l'oxygène sur l'azote".

traces of antiseptics. It shows a general increase up to a certain point with the amounts of moisture, organic matter and calcium carbonate present, although no sharp proportionality exists. It is related to productiveness; in a series of similar soils under similar climatic and other external circumstances the respective rates of oxidation were found to vary in the same way as the values for productiveness (Table XLVII.).

TABLE XLVII.—RATES OF OXIDATION, ORDER OF PRODUCTIVENESS, AND ANALYTICAL DATA FOR CERTAIN WOBURN SOILS. RUSSELL (241a).

| Name of Field. | Agricultural History. | Order of Productiveness. | Oxygen Absorbed in 17 days (mm.) | Analytical Data. | | | |
|-------------------|---|--------------------------|----------------------------------|------------------|---------|-------------------|--------------------|
| | | | | Nitrogen. | Carbon. | Loss on Ignition. | Calcium Carbonate. |
| Stiff Oxford clay | Wheat stubble | 1 | 23·2 | 252 | 2·53 | 8·73 | ·021 |
| Road Piece | Wheat stubble preceded by mangolds fed on the land | 2 | 18·7 | 172 | 1·76 | 5·31 | ·072 |
| Lansome field | Barley following mustard ploughed in; mineral manure | 3 | 14·1 | 122 | 1·19 | 4·17 | ·027 |
| Lansome field | Barley following tares ploughed in; mineral manure | 4 | 10·2 | 132 | 1·24 | 3·22 | ·051 |
| Lansome field | Barley following tares ploughed in; no mineral manure | 5 | 8·2 | 109 | 1·18 | 3·46 | ·008 |
| Stackyard field | Wheat unmanured | 6 | 8·2 | 106 | 1·39 | 4·07 | ·004 |
| Stackyard field | Wheat, ammonium salts only | 7 | 7·8 | 102 | 1·29 | 4·58 | nil |

The reasons for the connection between oxidation and fertility will become more evident as we proceed. In so far as oxidation is due to micro-organisms, its velocity obviously affords a measure of their activity; Wollny and later van Suchtelen¹ used the CO₂ evolution for the same purpose. But there is a more fundamental relationship. Oxidation affords, so far as is known, the chief source of energy for the numerous micro-organisms of the soil. Gillespie² has sug-

¹ Van Suchtelen, *Cent. Bakt. Par.*, 1910, 28, 45-89. See also F. G. Merkle, *J. Am. Soc. Agron.*, 1918, 10, 281.

² *Soil Sci.*, 1920, 9, 199.

gested an interesting distinction between high and low potentials in oxidation which may prove of value in investigations.

Stoklasa and Ernest (273*a*) found about 0.05 grm. CO₂ evolved per kg. of soil in 24 hours at 20° C. under aerobic conditions. Under anaerobic conditions the quantities were less.

The Decomposition of the Carbon Compounds.

Cellulose forms the chief constituent of the plant residues added to the soil, and its decomposition is probably the largest single process occurring in the soil, accounting for the chief part of the "humus" found. The classical investigations of Omelianski showed that both marsh gas and hydrogen arise under anaerobic conditions, such as obtain in swamps and ponds, but in normal soils the decomposition proceeds aerobically and without the evolution of these gases.

It is generally supposed that fungi, and particularly actinomycetes, play an important part in cellulose decomposition: McBeth (185*b, c*) has also described bacteria to which he attributes this change. The only organism that has been studied in detail is *Spirochaeta cytophaga* (Hutchinson and Clayton, 140*f*). This organism is distributed in soils; it is aerobic and very selective in its action, cellulose being the only compound with which growth was secured: it is indeed inhibited by many carbohydrates, especially those containing reducing groups. Its nitrogen requirements are met by simple compounds such as ammonium salts, nitrates, amino-acids, but not by higher compounds such as peptone (except in weak solution), gelatine, etc. The products of decomposition of cellulose include small quantities of volatile acids; mucilage soluble in ammonia but insoluble in acids, and which does not give rise to optically active compounds on hydrolysis; and a pigment apparently related to the carotin group: there is no obvious gas in the cultures.

The organism possesses certain morphological characteristics which explain some of the difficulties of previous investi-

gators : it passes through phases in its life history that give the appearance of wholly distinct organisms.

The Nitrogen Cycle.

The chemical investigations of the nitrogen cycle in soils have usually been confined to changes in the percentage of nitrogen and in the amount of nitrate present, and consequently they throw little light on the actual reactions taking place. Incomplete as they are, however, they have served a useful purpose by indicating the nature of the problem and furnishing material that has helped in unravelling the rather complex changes going on. Four cases have been studied :—

1. The simplest is that of an ordinary arable loam kept moist, aerated, and at 10° to 15° C.—these being normal conditions—free from vegetation and from the washing action of rain—these being abnormal conditions. A considerable formation of nitrate then takes place, about 3 per cent. per annum of the nitrogen being converted, and generally there is a small loss of nitrogen, presumably in the free state. How far the accumulation of nitrate would go under these circumstances has never been ascertained, because the experiment is necessarily very slow. Boussingault (48*b*) stated that in eleven years one-third of the nitrogen of a rich soil changed to nitrate, and about one-half of the carbon to carbon dioxide.

2. If the conditions are made more normal by exposing the soil (still kept free from vegetation) out-of-doors to the action of rain and weather generally, the nitrates do not accumulate but wash out, and can be detected in the drainage water. The soil thus loses nitrogen compounds, and in course of time the loss becomes very considerable. At Rothamsted a little plot of arable land $\frac{1}{1000}$ acre in extent has been kept free from vegetation by hoeing, but not otherwise disturbed, since 1870 ; it has now lost one-third of its original stock of nitrogen. The plot has been converted into a lysimeter by isolating it from the surrounding ground by cement partitions and then underdraining : the drainage water is all collected and analysed. At the end of forty-seven years the

amounts of nitrogen found as nitrate in the drainage waters were added up and found approximately to equal the total loss of nitrogen from the soil (Table XLVIII.).

The obvious uncertainty attaching to so prolonged an experiment is reduced in this case by the fact that the determinations were for the last twenty-eight years of the period made by the same analyst. Miller found that the rate of loss of nitrogen (estimated by the quantities of nitrates in the drainage water) was about 40 lb. per annum in the earlier years, and fell below 30 lb. and finally below 25 lb. per annum in the later years. The experiment is not fine enough to justify any discussion of the small balance, but it shows that the loss of nitrogen is *mainly* due to leaching out of nitrates.

TABLE XLVIII.—CHANGES IN NITROGEN CONTENT OF A SOIL KEPT FREE FROM VEGETATION FOR FORTY-SEVEN YEARS, BUT EXPOSED TO RAIN AND WEATHER. MILLER (200*b*), RUSSELL AND RICHARDS (241*k*).

| Per cent. of Nitrogen in Soil, top 9 inches. | | Lb. of Nitrogen per Acre, top 9 inches. | | | Nitrogen Recovered as Nitrate, 1870-1917. |
|--|------------|---|--------------|-------------------|---|
| In 1870. | In 1917. | In 1870. | In 1917. | Loss in 35 Years. | Lb. per Acre. |
| 146 | 099 097 | 3500 | 2376 2328 | 1124 1172 | 1247 ¹ 1200 |

It is unfortunate that this highly important experiment has not been repeated with other types of soil, because there is evidence that a richer soil would lose *more* nitrogen than is accounted for by the nitrates formed, the rest presumably escaping as gas.

Consideration of the curves for the rate of washing out of nitrate led Russell and Richards (241*k*) to suppose that there must be a nitrate immobiliser, probably certain organisms, functioning in soils even when uncropped, taking up a part of the nitrate formed and only slowly liberating it.

¹ After deduction of the amount brought down in the rain. The upper line of figures refers to the 20 inch and the lower to the 60 inch gauge. Some nitrate is no doubt contributed by the sub-soil.

3. When the conditions are made wholly normal by allowing vegetation to grow, some of the nitrate is taken up by the plant and only a part is washed away, the division depending on the favourableness of the conditions for plant growth. The absorption of nitrate by the plant is much greater, and the amount of nitrate in the drainage water is therefore much less, on the Rothamsted wheat plots where ample supplies of potassium salts and phosphates are present, than on the plots where these nutrients are less abundant and the crops smaller (Table XLIX.).

TABLE XLIX.—EFFECT OF PHOSPHATES AND POTASSIUM SALTS ON THE UTILISATION OF NITRATES BY PLANTS.

| Treatment. | Crop Yield per Acre per Annum. | | Nitrogen, Recovered in Crop, lb. per Annum. | Nitrogen Present as Nitrate in Drainage Water during Autumn, Parts per Million. | Per Cent. of N in Soil. | N lost from Soil, lb. per Annum. |
|--|--------------------------------|--------------|---|---|-------------------------|----------------------------------|
| | Grain, Bushels. | Straw, Cwts. | | | | |
| Ammonium salts containing 86 lb. N + No P or K salts | 16.0 | 14.75 | 33.5 | 17.8 | .106 | 67.5 |
| Abundant supplies of P and K salts. | 26.7 | 30.75 | 45 | 8.5 | .116 | 51 |

Part of the absorbed nitrate remains in the root and stubble, and is again added to the soil when the plant dies. Hence the percentage of nitrogen in the soil is higher where the conditions are favourable for the growth of plants than where, by the operating of some limiting factor, plants cannot make full growth and therefore leave untouched much of the nitrate to be washed away. It is this that accounts for the losses in fallow ground—losses that have been discussed by Lawes, Gilbert, and Warington (166*b*), by Russell (241*f*) and by von Seelhorst (258).

Most of the data hitherto accumulated are incomplete, because they refer only to crop results and take no account of nitrates washed out in the drainage water: fuller data have, however, been obtained in the lysimeter experiments of Gerlach

at Bromberg (104*c*), and they fully confirm the results set out above.

4. There is no reason to suppose that the amount of nitrogen in an uncultivated soil alters appreciably from year to year so long as the land is untouched. But directly ploughing and cultivation operations begin great losses of nitrogen set in, as shown by Shutt's analyses of the Indian Head soil, Saskatchewan (Table L.). In this particular case there is practically no drainage water, and therefore little or no washing away of nitrates, yet only one-third of the lost nitrogen is recovered in the crop. Snyder (268*b*) has given similar results for Minnesota soils, and Swanson for Kansas soils.¹

TABLE L.—LOSSES OF NITROGEN CONSEQUENT ON BREAKING UP OF PRAIRIE LAND, TOP 8 INCHES. SHUTT (265).

| | Per Cent. | Lb. per Acre. |
|--|-----------|---------------|
| Nitrogen present in unbroken prairie | 371 | 6940 |
| " " after 22 years' cultivation | 254 | 4750 |
| Loss from soil | | 2190 |
| Recovered in crop | | 700 |
| Deficit, being dead loss | | 1490 |
| Annual dead loss | | 68 |

The exhaustion of the soil is due, therefore, not to the removal of the crop, but to the cultivation.

Similar losses take place when heavy dressings of farmyard manure are repeatedly applied to land. One of the Broadbalk wheat plots receives annually 14 tons of farmyard manure per acre, containing 200 lb. of nitrogen. Only little drainage can be detected though considerable leaching out of nitrates may occur, but the loss of nitrogen is enormous, amounting to nearly 70 per cent. of the added quantity. Alongside is a plot receiving no farmyard manure, from which, in spite of drainage, there is no apparent loss (Table LI.).

¹ Kansas *Bulls.*, 199, 1914; 220, 1918. See also *Journ. Ind. Eng. Chem.*, 1915, 7, 529. Summaries of other results are given by A. W. Blair and H. C. McLean, *Soil Sci.*, 1917, 4, 283-293.

TABLE LI.—LOSSES OF NITROGEN FROM CULTIVATED SOILS, BROADBALK WHEAT FIELD, ROTHAMSTED, FORTY-SEVEN YEARS, 1865-1912.

| | Rich Soil, Plot 2, lb. per Acre. | Poor Soil, Plot 3, lb. per Acre. |
|---|-------------------------------------|-------------------------------------|
| Nitrogen in soil in 1865 . . . | 175 per cent. = 4,340 | 105 per cent. = 2,720 |
| Nitrogen added in manure, rain (5 lb. per annum) and seed (2 lb. per annum) . . . | 9,730 | 330 |
| Nitrogen expected in 1912 . . | 14,070 | 3,050 |
| Nitrogen found in 1912 . . . | 245 per cent. = 5,730 | 103 per cent. = 2,510 |
| Loss from soil . . . | 8,340 | 540 |
| Nitrogen accounted for in crops | 2,550 | 750 |
| Balance, being dead loss . . . | 5,790 | - 210 |
| Annual dead loss . . . | 123 | - 5 |

Experiments of this kind have led to the conclusion that some gaseous product is formed in addition to nitrates, and, as no sufficient amount of ammonia can be detected, it is supposed that gaseous nitrogen is given off. The conditions for this decomposition appear to be copious aeration, such as is produced by cultivation, and the presence of large quantities of easily decomposable organic matter. Now these are precisely the conditions of intense farming in old countries and of pioneer farming in new lands, and the result is that the reserves of soil and manurial nitrogen are everywhere being depleted at an appalling rate. Fortunately there are recuperative actions, but one of the most pressing problems at the present time is to learn how to suppress this gaseous decomposition and to direct the process wholly into the nitrate channel.

It is evident that there must be some recuperative agency or the stock of soil nitrogen, which is never very great, would long ago have disappeared in old countries. Experiment has shown that soil *gains* nitrogen when it is allowed to remain undisturbed and covered with unharvested vegetation as in natural conditions. On the Broadbalk field a third plot adjacent to the two already mentioned was in 1882 allowed to go out of cultivation and has not been touched since; it

soon covered itself with vegetation, the leaves and stems of which go to enrich the soil in organic matter. The gain in nitrogen is very marked, as shown in Table LII. The gain is much influenced by the amount of calcium carbonate in the soil, and is considerably less on another plot in Geescroft field

TABLE LII.—GAINS IN NITROGEN IN SOILS PERMANENTLY COVERED WITH VEGETATION—ROTHAMSTED SOILS LEFT TO RUN WILD FOR 22-24 YEARS. HALL (120f).

| | Broadbalk: CaCO_3 , 3.32 per Cent. | | | | Geescroft: CaCO_3 , 0.16 per Cent. | | | |
|---|---|-------|------------------------|-------|---|-------|------------------------|-------|
| | Carbon, per Cent. | | Nitrogen, per Cent. | | Carbon, per Cent. | | Nitrogen, per Cent. | |
| | 1881. | 1904. | 1881. | 1904. | 1883. | 1904. | 1883. | 1904. |
| 1st 9 inches | 1.14 | 1.23 | .108 | .145 | 1.11 | 1.49 | .108 | .131 |
| 2nd 9 inches | .62 | .70 | .070 | .095 | .60 | .63 | .074 | .083 |
| 3rd 9 inches | .46 | .55 | .058 | .084 | .45 | .44 | .060 | .065 |
| Approximate gain in nitrogen, lb. per acre | | | | 2200 | | | | 1400 |
| Lb. per acre per annum | | | | 91.7 | | | | 60 |

LAND LAID DOWN TO GRASS IN 1856 AND MOWN ANNUALLY (DR. GILBERT'S MEADOW, ROTHAMSTED).

| | 1856. | 1879. | 1888. | 1912. |
|--------------------------------|---------------------|-------|-------|-------|
| Per cent. of N in top 9 inches | [.152] ¹ | .205 | .235 | .338 |

where only little calcium carbonate is present; whether this is due to any specific action, or to the changed physical conditions brought out by decalcifying a soil, is not clear. Gains of nitrogen also take place on land covered with perennial grasses and clovers even when the crop is mown or grazed. On clay pastures dressings of basic slag have been found to increase the nitrogen content of the soil, whilst potassium salts, such as kainit, have had the same effect on sandy soil.

In all these cases leguminous plants are present in greatest extent where the gains in nitrogen are greatest, but they are not necessarily the only nitrogen fixers.

¹ Estimated.

Advantage is taken of this recuperative effect in all rotations by alternating the periods of arable cultivation with periods of "rest" in grass and leguminous crops. In the old Norfolk rotations one year in four was given up to clover,¹ in modern rotations the clover or "seeds" mixture is sometimes left for two or three years before it is ploughed up, so that the enrichment may become more marked. Mr. Mason at Eynsham Hall² considerably enriched in nitrogen some poor Oxford clay by the growth of lucerne. But the gain in nitrogen does not go on indefinitely; in course of time a point of equilibrium is reached, higher or lower according to the soil conditions, where further gains are balanced by losses, so that the nitrogen content remains constant.

Thus there is an upper as well as a lower limit to the nitrogen content of the soil, the actual values depending on the soil conditions. Between these limits the nitrogen content may be maintained at any desired level, high when the ground is left in grass and leguminous crops, low when the ground is continuously cultivated. Unfortunately, on our present knowledge it is impossible to maintain a high content of nitrogen on cultivated land except at a wasteful expenditure of nitrogenous manure.

Tentative determinations of some of these limits are:—

| | Black Organic Soils (containing more than 10 per Cent. of Organic Matter). | Chalk Soils. ³ | Loams. ³ | Sands. ³ |
|-------------------|---|---------------------------|---------------------|---------------------|
| Upper limit . . . | 1 | '42 | '25 | '20 |
| Lower limit . . . | '25 | '13 | '09 | '03 |

The reactions involved in all these changes are obviously complex, but they have been partially disentangled, and we can now pass on to a more detailed consideration of the separate changes.

¹ It was known to the Romans that vetches were a good preparation for wheat (*cf.* Virgil, *Georgics*, Book I., lines 73 *et seq.*).

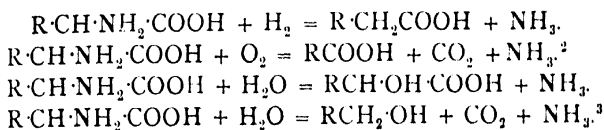
² *Journ. Roy. Agric. Soc.*, 1904, lxv., 106-124.

³ Containing less than 10 per cent. of organic matter

The Formation of Ammonia.

Ammonia is in all probability an intermediate product in the formation of nitrates. It is formed in the soil from the proteins of plant residues or manures, and the process is effected mainly by micro-organisms, but not entirely, for it still continues at a diminished rate in presence of antiseptics. The reaction has not yet been completely elucidated.

There is evidence of the production of amino acids which subsequently hydrolyse, or oxidise.¹ Although amino acids are in general fairly stable, several reactions are known whereby they may be decomposed with production of ammonia :—



It is not, however, known how they break down in the soil.

Miyake (202*b*) has shown that the rate of production of ammonia can be expressed by the equation for autocatalytic reactions, which means that it is much affected by the accumulation of the products. Both Gainey⁴ and Neller⁵ have studied the connection between the production of ammonia in soil and the evolution of CO₂.

The investigations by Marchal (190) in 1893 of the method of ammonia production in the soil are so complete that little has since been added to the facts he ascertained. Müntz and Coudon (207) had established the micro-organic nature of the process by showing that it was stopped by sterilisation. Marchal, therefore, made systematic bacteriological and mycological analyses of soils, and studied the action of the organisms thus obtained on solutions of albumin. Of the dozen

¹ See R. H. Robinson and H. V. Tartar, *J. Biol. Chem.*, 1917, **30**, 135-144.

² Dakin, *Four. Biolog. Chem.*, 1908, iv., 63; *Oxidation and Reduction in the Animal Body* (Longmans, 1912).

³ Ehrlich, *Zeitsch. Verein. Rubenzucker Ind.*, 1905, 539-567.

⁴ Gainey, *Soil Sci.*, 1919, **7**, 293.

. R. Neller, *Soil Sci.*, 1918, **5**, 225.

or so varieties that invariably occurred, practically all decomposed the albumin and formed ammonia. One of the *mycoides* group proved very vigorous and was studied in some detail. The process was considered to be a simple oxidation necessary to the life of the organism; oxygen was absorbed and carbon dioxide evolved, the ratio $\text{NH}_3 : \text{CO}_2$ produced being 1:8.9. For complete oxidation of the carbon, hydrogen, and sulphur of the albumin molecule the ratio would be 1:10.3; but the change was known to be incomplete, and small quantities of leucine, tyrosine, and fatty acids could also be detected. Free oxygen, however, was not essential. When grown in a culture solution containing sugar and nitrate the organism took its oxygen from the nitrate, but it still produced ammonia.

The energy relationships thus indicated were wholly overlooked by investigators for nearly a quarter of a century: it was not till 1916 that Doryland (86) showed their significance. The organism produces ammonia, not because it must, but because it can do so, and can leave ammonia in excess of its needs: its prime requirement is energy. If sources of energy other than proteins are supplied, *e.g.* carbohydrates, these may be used and then there is a decrease in ammonia production which may finally fall to nothing or become negative: the ammonia producers then become ammonia absorbers just like the higher plants, and indeed they compete with growing crops. It follows that no simple numerical expression can be given for the ammonification of organic matter: the true constant is the requirement of energy. This might be expressed in terms of protein if no other carbon compounds were present, but it is improbable that any equivalent could be worked out for the complex mixture in ordinary soils.¹

¹ For other experiments on the effect of carbohydrate in reducing ammonia production see H. M. Jones, *J. Infect. Dis.*, 1919, 19, 33, showing that *Bac. proteus* does not produce a proteolytic enzyme in presence of available carbohydrate; J. G. Lipman and Blair, *New Jersey Bull.*, 247, 1912, and *Annual Rept.*, 1914, p. 220, ammonia producing power of soil is diminished by carbohydrates; S. A. Waksman, *J. Amer. Chem. Soc.*, 1917, 39, 1503, similar effects are produced in cultures of *aspergillus*; I. J. Kliger, *Jour. Bact.*, 1, 663, and Berman and Rettger, *Jour. Bact.*, 1918, 3, 389.

Subsequent developments have been entirely on the bacteriological side. A number of organisms are now known to produce ammonia from complex nitrogen compounds, but soil bacteriologists, notably J. G. Lipman and his school at New Jersey, have generally preferred to study the group as a whole, rather than isolate and study individual members. The method consists in inoculating soil into various arbitrary culture media, each designed to favour one group only of organisms. Some of the results obtained are discussed in Chapter VII.; they show the method has value as a bacteriological test, but it has thrown little or no light on the processes going on in the soil. Indeed, so dependent is bacterial activity on temperature, concentration, reaction of medium (whether acid or alkaline), and other conditions, that it may be doubted whether any method of study, except in the actual soil itself, will further our knowledge of the reaction very much.

Of the few attempts to study the individual species of organisms concerned in ammonification H. J. Conn's is perhaps the most notable. Contrary to the accepted view he claims that ammonia formation is mainly brought about by non-spore formers: *B. mycoides*,¹ generally regarded as one of the most common ammonia producers in the soil, he dismisses as ineffective. He maintains that of the eight ammonifiers studied by Marchal only one, *B. fluorescens liq.* (a non-spore former), is a typical soil organism. He describes in detail two organisms, *Ps. fluorescens* and *Ps. caudatus*, which, while not very numerous in unmanured soil, multiply vigorously on addition of farmyard manure and also produce ammonia (70c). Waksman has adduced evidence (see p. 259) that fungi, and especially actinomycetes, are active ammonia producers in soil.

Nitrification.

The ammonia formed by the action of soil bacteria, or added in manures, is changed to carbonate, which is then rapidly converted by *Nitrosomonas* into nitrite, and this by

¹ Really a group, not a single organism.

Nitrobacter into nitrate, the changes proceeding so rapidly that only traces of ammonia or nitrite are ever found in normal arable soils (241*l*). We may, therefore, infer that the production of nitrates is the quickest of the three reactions, the production of nitrites is slower, while the formation of ammonia is the slowest of all and sets a limit to the speed at which they can take place. Thus a measure of the speed at which nitrates are formed in soil does not measure the rate of nitrification, as is sometimes assumed, but the rate of ammonia production.¹

The essential facts of nitrification are readily demonstrated by putting a small quantity of soil—2 to 5 grm.—into 50 c.c. of a dilute solution of ammonium sulphate containing nutrient inorganic salts and some calcium or magnesium carbonate, but no other carbon compound.² After three or four weeks at 25° the ammonia has all gone and its place is taken by nitrates. The conversion is almost quantitative, only an insignificant quantity of nitrogen being retained by the organisms.

The course of the oxidation is unknown, and nothing intermediate between ammonia and nitrous acid has been detected. On general grounds one would look for hydroxylamine. A. Bonazzi³ has made the significant observation that nitrification in culture solutions is intensified by thorough aeration or continuous motion of the culture medium.

Miyake has shown (202*b*) that the reaction resembles autocatalysis in its course. Omelianski could obtain no evidence of an oxidase in *Nitrosomonas* (219*c*). The action of both organisms seems to be entirely specific. *Nitrosomonas* oxidises ammonium carbonate and nothing else; it will not touch nitrates, urea, or the substituted ammonias. Even

¹ See also P. L. Gainey, *Soil Sci.*, 1917, 3, 399-416.

² Omelianski (219*b*) used 2 grms. each $(\text{NH}_4)_2\text{SO}_4$ and NaCl, 1 grm. KH_2PO_4 , 5 MgSO_4 , 4 FeSO_4 in 1 litre of water, and added 5 grm. MgCO_3 for each 50 c.c. of solution used. Nitrite formation goes on in this solution. For nitrate production he used 1 grm. each NaNO_3 and Na_2CO_3 , 5 each KH_2PO_4 and NaCl, 4 FeSO_4 and 3 MgSO_4 in 1 litre of water. Ashby (7*a* and *b*) found that both processes went on simultaneously when he diluted the first of these solutions to one quarter the strength.

³ A. Bonazzi, *J. Bact.*, 1919, 4, 58.

ammonium salts are nitrified only in presence of a carbonate that can change them into ammonium carbonate (296). Nitro-bacter is equally specific, oxidising nitrites only and not ammonia.

Addition to the solution of almost any carbon compound other than calcium or magnesium carbonates retards the rate of nitrification, glucose and peptone being particularly harmful (311*b*). Carbon dioxide suffices as the source of carbon for the growth of the organism. Godlewski¹ showed that nitrification proceeds in solutions free from organic matter so long as the air supplied contained carbon dioxide, but stops as soon as the carbon dioxide is removed by passage over caustic potash. But the synthesis of complex cell substances from carbon dioxide is an endothermic process requiring a supply of energy. In the case of the green plant—the only other living thing known to utilise carbon dioxide—the energy comes from light, the transformer being chlorophyll. Here, however, light is out of the question, and is even fatal to the organism. Winogradsky (311*a*) suggested that the necessary energy is afforded by the oxidation of ammonia and of the nitrite, and he traced a definite relationship between the amount of ammonia oxidised and the carbon assimilated.

| | Experiment 1. | Experiment 2. | Experiment 3. | Experiment 4. |
|--|---------------|---------------|---------------|---------------|
| Ammonia oxidised (expressed as nitrogen) . | 722.0 mg. | 506.1 mg. | 928.3 mg. | 815.4 mg. |
| Carbon assimilated . | 19.7 „ | 15.2 „ | 26.4 „ | 22.4 „ |
| Ratio $\frac{N}{C}$ | 36.6 „ | 33.3 „ | 35.2 „ | 36.4 „ |

In these experiments mixed cultures were used, the nitrate producers predominating. More recently Coleman (68), using pure cultures of nitrate producers, obtained ratios varying from 40 to 44 for the second stage of the process.

No useful hypothesis has yet been put forward to account

¹ Quoted in Lafar, *Tech. Mykologie*, 1906, Bd. 3, 165.

for these remarkable facts. The whole subject deserves serious attention from some competent chemist.

It was somewhat hastily inferred that organic matter would have a retarding effect in the soil just as it has in culture solutions. From the outset, however, certain facts were known to be against this view: thus, there was a good deal of organic matter in the old nitre beds (235) and also in rich gardens, and yet nitrification went on vigorously in both cases. An exception was therefore made in favour of "humus" (208). Later on Adeney (2), and again Miss Chick (66), found another exception: the organic matter of the filter beds used in sewage purification. Richards finds that nitrification proceeds very vigorously during the activation of sludge by aeration. Coleman has now shown (68), and Stevens and Withers (271*b*) have confirmed it, that *only in culture solutions* is organic matter injurious: in the soil it does no harm, and may even help the process. Thus quantities of dextrose that stopped nitrification entirely in Winogradsky and Omelianski's culture solutions were found to act beneficially in soil under normal conditions of temperature and moisture content. The discrepancy cannot yet be explained. Sucrose, lactose, and certain other non-nitrogenous compounds had no effect, but nitrogenous compounds were distinctly injurious.

The organisms will not tolerate an acid medium; a sufficient excess of calcium carbonate is therefore necessary both in culture solutions and in soils. Nor will they tolerate free ammonia. In culture solutions the nitrate producer is somewhat sensitive even to ammonium salts, indeed both Warington (296) and Omelianski (219*b*) suppressed it by maintaining a sufficient concentration of ammonium sulphate; Löhnis has shown, however (181*a*), that it is more tolerant in the soil. Some substance toxic to them is produced when soil is heated to 98° C. or more, and in such soils they cease to act. Neither nitrosomonas nor nitrobacter has been observed to form spores, or to survive temperatures above 45° C., or treatment with mild antiseptics like carbon disulphide and toluene. But so widely distributed are they and so readily can they spread

in the soil, if the conditions are at all favourable, that they may reappear unless special precautions are taken to prevent infection. Thus, it is commonly stated that treatment of the soil with carbon disulphide merely depresses without killing the organisms. Russell and Hutchinson found, however, that the organisms did not reappear if the soil was kept carefully free from re-infection (241c).

In pure cultures the organisms cannot tolerate absence of moisture, but die at once. In soil, however, they are more resistant. Absence of air puts an end to their activity.

There is some evidence that nitrobacter is more sensitive to adverse circumstances than nitrosomonas; it is also more rapid in action. Otherwise the two sets of organisms show very similar behaviour to external influences, their main difference being the fundamental one that nitrosomonas oxidises ammonia, but not nitrites, while nitrobacter oxidises nitrites, but not ammonia. There are also certain morphological differences. Nitrosomonas, or coccus, occurs in several forms, mostly oval in shape, 0.5 to 1 μ wide and up to 2 μ long, but whether these are really distinct varieties is not known; a zooglea stage is also found; nitrobacter is rod-shaped, 1 μ long and about 0.3 μ thick; only one variety has been recognised. No other organisms are known with certainty to produce nitrates in the soil, nor can any other compound except ammonia be nitrified (219a).

During the course of nitrification some calcium is dissolved, but apparently no phosphate, except in culture solution.¹

The Evolution of Gaseous Nitrogen.

It has long been known that losses of nitrogen may occur during the bacterial decomposition of organic matter which cannot be attributed to the volatilisation of ammonia, and which, therefore, are put down to an evolution of gaseous nitrogen: instances are afforded by manure heaps, by rich

¹ Kelley, *Journ. Agric. Res.*, 1918, 12, 682. But see Hopkins and Whiting (*Ill. Bul.*, 190, 1916), who maintain that phosphate is rendered soluble during nitrification.

soils, and by sewage beds. The observations go back to the time when the sources of nitrogen for vegetation were being investigated, and attempts were made to set up a balance sheet showing the relation between the amounts of nitrogen in the plant and the soil at the beginning and at the end of its growth respectively. Reiset,¹ Ville (2886), and Boussingault (45) sometimes found less nitrogen in soil + plant at the end of an experiment than in soil + seed at the beginning, and attributed the difference to an evolution of free nitrogen. Some of these early observations were probably faulty by reason of the crudeness of the analytical methods, but Lawes, Gilbert, and Pugh (164) showed that losses of nitrogen undoubtedly took place sometimes, though not always, when nitrogenous organic matter, wheat-meal, barley-meal, or bone-meal, was made into an "agglutinated condition" with water, and allowed to decompose in presence of air. Practically no ammonia could be detected. Lawes and Gilbert suggested three possible reactions, a suggestion that still holds the field.

1. An oxidation analogous to that of the action of chlorine on ammonia, by which free nitrogen is evolved.

2. A reduction similar to that of a great number of substances upon the oxygen compounds of nitrogen, by which the oxygen is appropriated and the nitrogen set free.

3. These two actions may operate in succession the one to the other.

Little attention was paid to these results at the time, but later on losses of nitrogen were found to occur in the purification of water and of sewage. Angus Smith² in 1863 observed an evolution of gaseous nitrogen from a dilute solution of putrefying blood, and showed that nitrates gave off nitrogen under certain circumstances. The earlier sewage workers, Frankland,³ and others, did not actually mention any loss of

¹ Reiset, *Jahresbericht der Chemie*, 1856.

² Angus Smith, *Memoirs Manchester Lit. and Phil. Soc.*, 1863, 1867-8, Vol. IV.; also *Report to the Local Govt. Board*, 1882.

³ Frankland, Denison, and Chalmers Morton, *Royal Commission, Pollution of Rivers*, 1868, Vols. 1-4.

nitrogen during sewage purification though the published results show that it occurred. Later sewage workers recognised the loss, and Letts, indeed, made measurements of the evolved nitrogen, special gasimetric methods being devised for the purpose.¹

A serious attempt to grapple with the problem was made in 1896 and 1897 at some of the German Experiment Stations, notably Jena, in consequence of the request made by the German Agricultural Society for an investigation into the losses of nitrogen from farmyard manure. The first hypothesis, set up by Wagner, was a reduction hypothesis to the effect that nitrates are present in the manure, and decompose in absence of air, giving rise to nitrogen. This view, however, soon proved to be erroneous, for it supposed that the loss only occurred in absence of air, whereas, in point of fact, it only occurs in presence of air.

Immendorf (141*a*) recognised this fact and favoured the oxidation hypothesis, considering that evolution of nitrogen was the result of direct oxidation or combustion of the nitrogen compounds to gaseous nitrogen. No reduction of nitrate was assumed. Pfeiffer and his assistants at Jena (224*a*) began on the reduction hypothesis, and supposed that nitrates were formed on the outside of the heap and then diffused inside, where they were denitrified. But during the course of their experiments they changed their view, and ended by accepting the oxidation hypothesis.

Two lots of cow manure (made with peat) were put up: air was blown through one, and over the other. The losses of nitrogen were:—

| | Grams. | Per Cent. |
|---------------------------|--------|-----------|
| Air blown through | 4.26 | 42.6 |
| " " over | 2.76 | 27.6 |

They argue that blowing air over the dung would be favourable to their supposed nitrification and denitrification process, while blowing air through would be unfavourable

¹ Letts, *Fifth Report, Sewage Commission*, Appendix 6, 171-194; also *Report to the Corporation of Belfast on the Purification of Belfast Sewage*.

to it since denitrification requires an absence of air. Yet blowing air through the dung causes greater loss. Again, nitrogen may be lost where no nitrification is observed, and further, the effect of antiseptics on the extent of the loss is not what might be expected from a knowledge of their effect on denitrifying organisms. In consequence of these results they gave up the alternate oxidation and reduction hypothesis and accepted the direct oxidation hypothesis. Some support was lent to this direct oxidation view by the announcement that Wood and Wilcox¹ had isolated from bran infusions an organism able to liberate nitrogen direct from nitrogenous compounds: apparently, however, this has not been confirmed.

On the other hand, Müntz and Lainé (208*c*), working on sewage purification, and dealing with percolation filters, reject the oxidation hypothesis. In the first instance they note that loss occurs only in presence of organic matter: it is not seen when a solution of ammonium salts is run on to the filter. Secondly, they find that the addition of nitrate to the liquor increases the loss of nitrogen. Laboratory experiments showed that it caused an evolution of nitrogen, and by working in a vacuum a complete balance was made as follows:—

| | At Start. | At End. |
|----------------------------------|-----------|-----------|
| Nitrogen as ammonia | 16·3 | 15·2 mgs. |
| „ in organic compounds | 12·2 | 13·1 |
| „ as nitrite | 1·2 | 0·5 |
| „ as nitrate | 30·6 | 8·0 |
| Total | 60·3 | 36·8 |
| Loss | — | 23·5 |

But they found dissolved in the liquid:—

Free nitrogen 38·1 c.c. at N.T.P. = 23·9 mgs., which thus almost exactly balances the loss.

This experiment shows that denitrification can take place and cause loss of nitrogen, though it does not necessarily exclude the hypothesis of a direct oxidation of ammonia.

Adeney's (2) results are also inconsistent with the direct oxidation hypothesis. When albuminose, asparagin, etc., are

¹ *Journ. Soc. Chem. Ind.*, 1897, 16, 510.

decomposed by bacteria in dilute solutions saturated with oxygen there is no loss of nitrogen. Russell and Richards (241*k*) were also unable to find any loss of nitrogen in the aerobic fermentation of urine or fæces, even though in the case of urine considerable nitrification occurred.

The present position of the problem, therefore, is that this loss of nitrogen does not occur under anaerobic conditions, nor under aerobic conditions; it requires a combination of both, such as obtains in manure heaps, in rich soils and in the system of beds and filters in a sewage works.

These facts are inconsistent with either a direct oxidation or a direct reduction process; both Wagner's and Immendorf's hypotheses, therefore, are ruled out. They are consistent with Müntz's alternate nitrification and denitrification hypothesis, but they do not prove it. Russell and Richards have given a more general explanation, which seems to be free from some of the mechanical objections that can be urged against alternate nitrification and denitrification. They suppose that molecular groupings arise under anaerobic conditions which become unstable as soon as aerobic conditions set in, and decompose, splitting off nitrogen. The change is parallel to the shortening of the propionic acid chain with formation of an acetic acid derivative, which is known to take place in these conditions.¹

Although the investigations have been mainly on manure heaps and sewage beds there is evidence that the same process occurs in heavily manured soils and in virgin soils rich in organic matter brought into arable cultivation, and that it causes the losses already discussed on p. 181.

The Fixation of Nitrogen.

The first systematic search for a recuperative agency to make good the losses of nitrogen from the soil was started thirty years ago by Berthelot. He found that certain organic

¹ See Barger, *The Simple Natural Bases* (Longmans' Biochemical Monographs), where various instances are given.

compounds could absorb free nitrogen under the influence of silent electric discharges, and at first attributed the natural recuperation to this cause. He also examined the possibility of bacterial action, as micro-organisms at that time were playing a large part in French science under Pasteur's influence. Accordingly he exposed sterilised and unsterilised sands and clays poor in nitrogen (0.1 per cent. or less) to air in large closed flasks for five months, and found distinct gains in nitrogen in the unsterilised, but not in the sterilised soils. Fixation is, therefore, not due to any external physical cause, which would operate equally in both cases, but to micro-organisms (26). This research was at once fruitful of results because it gave Hellreigel and Wilfarth the key to the clover problem (p. 25), and led Winogradsky (312) to search for the actual organism.

No investigator of our subject has shown greater enuity than Winogradsky in devising methods at once simple, direct, and effective. In looking for the nitrogen-fixing organisms he inoculated soil into a medium containing every nutrient except nitrogen compounds: only bacteria capable of assimilating gaseous nitrogen could therefore develop, and these had a clear field. But he further recognised that the process was endothermic and required some source of energy, hence he added sugar to the solution. The method (known as the elective method) thus consists in making the conditions as favourable as possible for the group of organisms under investigation, and as unfavourable as possible for all others; it has proved extremely valuable in the subsequent development of soil bacteriology.

Winogradsky's solution contained 2 to 4 per cent. dextrose, a little freshly washed chalk, 0.1 per cent. K_2HPO_4 , 0.05 of $MgSO_4$ and traces of $NaCl$, $FeSO_4$, and $MnSO_4$, together with a little soil. Under aerobic conditions nitrogen was assimilated and the sugar was decomposed with evolution of carbon dioxide and hydrogen and formation of n-butyric and acetic acids in the proportion of three or four molecules of the former to one molecule of the latter, the two acids together

accounting for nearly half the sugar. A little alcohol was found, but practically no non-volatile acid. There was a distinct relationship between the amount of nitrogen assimilation and the sugar decomposed, each milligram of nitrogen fixed requiring the oxidation of about 500 milligrams of sugar.

Three organisms were present, a clostridium and two bacteria, and they obstinately refused to be separated by the method of successive cultures. Not until recourse was had to anaerobic conditions were the two bacteria suppressed and the clostridium obtained pure. The bacteria having been isolated, it appeared that the clostridium alone possessed the power of fixing nitrogen, but a fresh difficulty now arose because in pure cultures the organism would *work only under anaerobic conditions*. Only when the protective bacteria were simultaneously present did fixation go on in presence of air. The organism was called *Clostridium pasteurianum*:¹ it formed rods 1.2 μ thick and 1.5 to 2 μ long and also spores (312).

In order to simplify the bacterial flora Winogradsky had heated his soil to 75°, thereby killing non-spore formers, but later on Beijerinck (14 and 15), working with unheated soil discovered three other nitrogen-fixing organisms; *Azotobacter chroococcum* (so called because, as it ages, it turns brown and finally almost black), *Granulobacter* and *Radiobacter*.² Of these *azotobacter* is the most active; it forms large cocci, or rods, 4 to 6 μ in thickness.³ It differs in two important respects from clostridium: (1) it is aerobic; (2) it produces practically no butyric acid. Its effects can be studied by inoculating 0.1 to 0.2 grm. of soil into 100 c.c. of tap water containing 2 per cent. mannitol, .02 per cent. K_2HPO_4 , and sufficient $CaCO_3$, and keeping for some weeks at 27° to 30° C. in a thin, well-aerated layer⁴ in an Erlenmeyer flask. *Azotobacter* fixed

¹ For further investigation of clostridium see Omelianski, *Rome Bull.*, 1917, 8, 1190.

² Since shown by Stoklasa (275b) to possess only slight nitrogen-fixing power.

³ Löhnis and Smith describe cyclical changes through which *azotobacter* is considered to pass (*Journ. Ag. Res.*, 1916, 6, 675).

⁴ Later on Beijerinck used calcium malate in place of sugar, and showed also how to make plate cultures of the organisms (16).

more nitrogen than clostridium per grm. of sugar decomposed.

The nature of the compound is also important. Table LIII. gives the amounts of nitrogen fixed per grm. of compound decomposed.

TABLE LIII.—MGMS. OF NITROGEN FIXED BY AZOTOBACTER PER GRM. OF SUBSTANCE DECOMPOSED.¹ LÖHNIS AND PILLAI (181d).

| Mg. of Nitrogen Fixed. | |
|------------------------|--|
| 7.5 to 10 | Mannitol, xylose, lactose, lævulose, inulin, galactose, maltose, dextrin, sucrose + calcium carbonate. |
| 5 to 7.5 | Sucrose alone, dextrose, sodium tartrate + calcium carbonate, glycerol + calcium carbonate. |
| 2.5 to 5 | Starch, sodium tartrate, sodium succinate, calcium lactate. |
| 1 to 2.5 | Sodium propionate, sodium citrate, glycerol alone. |
| Nil | Calcium butyrate, potassium oxalate. |

GERLACH AND VOGEL (104b).

| | | | | | | | | | | |
|--|-------|-------|-------|-------|-------|-------|-------|--------|--------|---------------------|
| Glucose decomposed, mgs. . | 1,000 | 2,000 | 3,000 | 4,000 | 5,000 | 6,000 | 7,000 | 10,000 | 12,000 | 15,000 ² |
| Nitrogen fixed, mgs. . . | 7.4 | 13.5 | 17.8 | 31.4 | 39.4 | 45.9 | 59.9 | 91.4 | 127.9 | 62.9 |
| Nitrogen fixed, per grm. of sugar . . | 7.4 | 6.8 | 5.8 | 7.8 | 7.9 | 7.6 | 8.5 | 9.1 | 10.7 | — |
| Mean 8.9 mgs. nitrogen fixed for 1 grm. sugar. | | | | | | | | | | |

Little is known of the chemistry of the process, even the fate of the sugar has not been definitely ascertained. The only obvious product is carbon dioxide, fatty acids being formed only in small quantities, in sharp contrast with clostridium.

Starting with 15.9 grms. of dextrose Stoklasa (275b) recovered 7.9 as carbon dioxide, 0.3 as ethyl alcohol, 0.2 as formic acid, 0.7 as acetic acid, 0.2 as lactic acid, but could not trace the remaining 6.5 grms.

¹ For list of other substances see F. A. Mockeridge, *Biochem. Journ.*, 1915 9, 272-283.

² The sugar was not all used up in this experiment.

The energy relationships are equally little known: it is concluded, however, that only about 1 per cent. of the total available energy is utilised in the fixation of nitrogen.¹

Beijerinck's solution works satisfactorily for crude cultures but not for pure cultures. Various hypotheses have been put forward in explanation; it was supposed that azotobacter required the presence of some other organism, or that it lost its efficiency on cultivation. Krzemieniewski (157) found that neither of these views is correct, and in an important investigation showed that the determining factor is the presence of a little soil; so long as this is added pure cultures retain their effectiveness. The active agent is the humus, but its effect is not to furnish carbon or nitrogen to the organism; further, the humus loses its power after treatment with hydrochloric acid. Remy and Rösing (237*b*) frankly call it a stimulating action and attribute it to the iron invariably present.² Allen,³ on the other hand, supposes that the colloids of the humus prevent complete precipitation of the phosphate and thus facilitate phosphorus nutrition of the organism.

The nitrogen is found partly in compounds dissolved in the liquid, but mostly in the bacterial mass. The organism is remarkably active, one grm. weight evolving no less than 1.3 grms. of CO₂ in twenty-four hours (273*a*). An adequate supply of phosphate, calcium carbonate and other mineral nutrients is essential, any deficiency limiting the amount of fixation. Traces of nitrogen compounds are helpful in the early stages, but larger quantities reduce the amount of fixation, and may themselves suffer some change: thus sodium nitrate is partially reduced to nitrite even under aerobic conditions (Stoklasa (275*b*)). Hills (134) finds that the beneficial effect of small quantities of nitrate of soda and nitrate of potash is not confined to the growth of the organism, but extends (though to a less extent) to fixation also, and it is

¹ G. A. Linhart, *Journ. Gen. Physiol.*, 1920, 2, 247-251.

But see also Reed and Williams, *Centr. Bakt. Par.*, 1915, 43, 166.

E. R. Allen, *Ann. Mis. Bot. Garden*, 1919, 6, 1.

shown both in culture solutions and in soil.¹ Several forms of azotobacter are now known: *A. agilis*, *A. vinelandii*, etc., and also various less efficient nitrogen fixers that more resemble clostridium, such as amylobacter (52) and granulobacter, some of which are aerobic and others anaerobic.² The great distinction between the two groups is that the azotobacter give carbon dioxide as the chief product from the sugar, while the others, even the aerobic organisms, form butyric acid in considerable amount and fix smaller quantities of nitrogen. Amylobacter also makes and stores glycogen, a property possessed by few other micro-organisms.

Kossowitch (154a) has shown that a mixture of azotobacter and algæ, especially nostoc, can work together very well, the algæ furnishing the necessary carbon compounds, while the azotobacter fixes nitrogen, an observation that has been confirmed by Bouillac (43 and 44). Sand has been found to gain nitrogen where the growth of algæ was possible and the proper bacteria were present.³ Evidence is now being adduced that some of the algæ can fix nitrogen by themselves, and without the co-operation of azotobacter⁴ (p. 255).

How far azotobacter is active in the soil in natural conditions has not been definitely ascertained, partly because of the analytical difficulties of measuring small gains of nitrogen, and partly because of the losses of nitrogen that, as we have seen, go on in presence of organic matter. The mere occurrence of azotobacter in the soil is no proof that it is actually fixing nitrogen, the only satisfactory evidence would be a demonstrated gain in nitrogen effected by azotobacter, all other possibilities being ruled out by the experimental conditions. The usual method of investigation has been to add sugar, or other carbohydrates, to the soil and measure the change in nitrogen content after various intervals of time.

¹ D. A. Coleman obtained less fixation in presence of nitrate (*Soil Sci.*, 1917, 4, 345).

² A list is given by C. B. Lipman in *Journ. Biol. Chem.*, 1911, x., 169-182.

³ A. Koch has collected instances in Lafar, *Tech. Mykologie*, Bd. iii., p. 15.

⁴ B. Moore and T. A. Webster, *Proc. Roy. Soc.*, 1920, B 91, 201.

Generally, there is a gain of nitrogen; losses are, however, often recorded (248, 151, etc.), whilst a certain loss of nitrate invariably occurs (p. 266). A. Koch (151*b*) added successive small doses of dextrose to 500 grms. of loam, mixed with sand and spread on plates to secure copious aeration, kept uniformly moist and at 20° C. Nitrogen fixation began very soon and reached its maximum after eighteen weeks, when losses set in; the results are given in Table LIV.

TABLE LIV.—NITROGEN FIXED IN SOIL BY BACTERIAL ACTION IN PRESENCE OF DEXTROSE. KOCH (151*b*).

| Increments of Dextrose per 100 grms. of Soil. | Total Dextrose Supplied in grms. per 100 grms. of Soil after | | | | Mgns. N fixed per 100 grms. of Soil after | | | |
|--|---|----------|-----------|-----------|--|----------|-----------|-----------|
| | 5 Weeks. | 8 Weeks. | 18 Weeks. | 26 Weeks. | 5 Weeks. | 8 Weeks. | 18 Weeks. | 26 Weeks. |
| | June 26. | July 20. | Oct. 3. | Nov. 30. | June 20. | July 20. | Oct. 3. | Nov. 30. |
| 2 | 1.0 | 1.6 | 3.6 | 5.2 | 8.3 | 14.9 | 17.8 | 18.9 |
| 5 | 2.5 | 4.0 | 9.0 | 13.0 | 20.1 | 32.5 | 36.8 | 31.6 |
| 10 | 5.0 | 8.0 | 18.0 | 26.0 | 35.8 | 57.2 | 58.7 | 52.7 |
| 15 | 7.5 | 12.0 | 27.0 | 37.5 | 40.5 | 66.7 | 68.5 | 66.8 |
| 20 | 8.0 | 14.0 | 26.0 | 36.0 | 43.9 | 78.8 | 80.0 | 78.8 |

For each gm. of dextrose supplied in the small doses about 8 milligrams of nitrogen were fixed during the first eight weeks; but only 4 or 5 milligrams later on. In larger doses the sugar was less effective, only 5 to 6 milligrams of nitrogen being fixed per gm. of sugar at first and 3 milligrams later.

Pot experiments showed that the nitrogen thus added to the soil became available for plant food. Dextrose and sucrose first depressed the crop, then caused an increase, and finally left the soil richer in nitrogen at the end of the experiment than at the beginning (Table LV.).

But if the soil temperature fell too low nitrogen fixation ceased: it was not observed at 7° C. although it appeared to go on at 15° C. The optimum temperature lies between 25° and 30° C.

Pfeiffer and Blank (224*c*), however, were unable to obtain any beneficial results from sugar. The Rothamsted trials

showed increases for autumn applications but decreases for spring dressings (140e).

TABLE LV.—EFFECT OF DEXTROSE AND SUCROSE ON THE PRODUCTIVENESS AND NITROGEN CONTENT OF THE SOIL. KOCH (151b).

| Sugar added per 100 grms. of Soil. | Crops Obtained. | | | | Total N Removed in Crop. | Nitrogen Left in Soil, Spring, 1906. | |
|---------------------------------------|-----------------|----------------|-----------------------|----------------|--------------------------------|---|---|
| | Oats, 1905. | | Sugar Beets, 1906. | | | Total N per Cent. | N as Nitrates, Parts per Million. |
| | Dry Matter. | Yield of N. | Dry Matter. | Yield of N. | Grms. | | |
| | 100 | 100 | 100 | 100 | 0.5914 | .093 | 10 |
| 2 per cent. dextrose . | 32.8 | 62.5 | 186 | 190 | 0.6814 | .105 | 17 |
| 2 " " cane sugar | 33.3 | 58.7 | 179 | 195 | 0.680 | .105 | 15 |
| 4 " " " " | 37.7 | 78.1 | 283 | 339 | 1.0092 | .119 | 37 |

Increased yields of sugar cane have followed the application of molasses to soils at the Station Agronomique and on Mr. Ebbels' estate¹ in Mauritius, where the residual effect is well shown, and also in Antigua.² Peck in Hawaii, on the other hand, observed marked losses of nitrate, as also did Harrison in British Guiana.³

An increase in crop following the application of sugar or starch to the soil is not evidence of nitrogen fixation, but might equally well be adduced to show that sugar and its decomposition products are direct plant nutrients. Only when an actual gain in nitrogen is demonstrated by analysis does the proof become satisfactory. As a practicable scheme the addition of sugar to the soil would be out of the question for field work. Beijerinck (15) has shown, however, that certain compounds producible in the decomposition of cellulose also serve as sources of energy to azotobacter, and Pringsheim (232) found that the same holds true for clostridium also.

Hutchinson (140e) has shown that leaves, stubble, etc.,

¹ See *The Agricultural News*, 1908, vii., 227; 1910, ix., 339; and 1911, x., 179.

² See *Manurial Experiments with Sugar Cane in the Leeward Islands*, 1908-09 and 1909-10. (Pamphlets 64 and 68, West Indian Department of Agriculture.)

³ *West India Bull.*, 1913, 13, 136. This contains an interesting discussion on the losses of nitrogen from soil.

serve to increase nitrogen fixation, though under other conditions they can, like sugar, depress the nitrate content of the soil. Doryland¹ has discussed the possibility of using various waste substances as energy supply, and Emerson² has discussed the prospect of soil inoculation with azotobacter.

Richards (238a) has made the interesting observation that animal faeces also serve for the organism both in culture and in more natural conditions, but there is a sharp connection between the diet and the effect. Horses fed on oats gave faeces which induced the greatest fixation: horses in grass came next: cattle receiving cake were next, while the faeces from cattle fed on grass proved unsuitable.

The difficulty of material might therefore be overcome because large quantities of cellulose are available on the farm in the form of straw. But there still remains the question of temperature. Azotobacter, as we have seen, requires more warmth than many other organisms, and according to Koch's experiments ceases to work at 7° C. Thiele read temperatures daily for three years of arable and grass soils at different depths at Breslau (281), and concluded that only rarely were they favourable for azotobacter. But it is impossible to argue from a culture solution to the soil, and, indeed, Löhnis has shown that the mixed cultures of the soil are almost as effective at 10° as at 20°.³

It seems legitimate to conclude that azotobacter fixes nitrogen in well-aerated soils sufficiently provided with calcium carbonate, potassium salts and phosphates, carbonaceous material of the right kind and moisture, so long as the temperature is high enough. Where the air supply is diminished owing to the close texture of the soil there is still the possibility of fixation by clostridium. Ashby (7c) found

¹ *Sci. Proc. Soc. Amer. Bacteriologists*, 1918.

² *Iowa Research Bul.*, 45, 1918.

³ *Mitt. Landw. Inst.*, Leipsic, 1905, vii., 94.

| | | |
|------------|------------|--------------------------|
| 10°-12° C. | 20°-22° C. | 30°-32° C. |
| 3'15 mg. | 4'55 mg. | 4'27 mg. nitrogen fixed. |

that the relative distribution of azotobacter and clostridium at Rothamsted depended on the amount of calcium carbonate in the soil; wherever any notable quantity was present, azotobacter invariably occurred: otherwise clostridium alone was found. This result appears to be general.¹ Remy suggested in 1906 that azotobacter was a good organism for the bacterial diagnosis of soils—absence showing some harmful factors and a rich development showing favourable conditions. Christensen (67*a*) gave definite form by designing a workable method (see p. 242), while Gainey² has ascertained that azotobacter occurs in soils with a P_H value 6.0 or more, but not in those with P_H value 5.9 or less.

Nitrogen Fixation by Bacteria in Symbiosis with Leguminosæ.

After Hellriegel and Wilfarth's great discovery of the relationship between bacteria and leguminosæ (p. 24) many unsuccessful attempts were made to isolate and study the organisms by the methods then in vogue. In 1888 Beijerinck (13) broke away from the ordinary meat-bouillon-gelatin plate and substituted a slightly acid medium made up of infusion of pea leaves, gelatin (7 per cent.), asparagine (25 per cent.) and sucrose (5 per cent.). Growth readily took place and the colonies yielded rods $1\ \mu$ wide and 4 to $5\ \mu$ long, some of which showed signs of bacteriod formation, and "swarmers" $0.9\ \mu$ long and $0.18\ \mu$ wide, these being among the smallest soil organisms known.³

The life cycle has been shown by Bewley and Hutchinson (36) to include non-motile and motile stages: conditions were ascertained under which one passed into the other.

¹ Hugo Fischer (1905) found azotobacter on the limed plots at Bonn-Poppelsdorf but not on the unlimed. Burri (1904) found it in only one-third of the Swiss soils examined.

² *Journ. Agric. Res.*, 1918, 14, 265. E. B. Fred and A. Davenport found the limits in culture solutions to lie between 6.5 and 8.6 (*Journ. Agric. Res.*, 1917, 14, 317).

³ Golding has shown that they will even pass through a porcelain filter and has prepared pure cultures in this way.

C. B. Lipman and L. W. Fowler¹ have succeeded in isolating the organism from soil, and T. F. Manns and Goheen² also claim to have done so.

The mode of entry into the pea was studied by Prązmowski (227), and later by Nobbe and Hiltner (215*b*). The organism—presumably in the swarmer stage—attacks the root hair, secreting a substance which causes the root tip to curl up; the membrane of the hair becomes swollen and the bacteria then penetrate.³ A filament, known as the infection thread, and shown to be formed of rapidly multiplying bacteria, gradually extends up into the root where the nodule begins to form; beyond this, the organisms do not penetrate. The morphological changes have been described by Marshall Ward (294), Miss Dawson (80) and others. Soon the organisms surround themselves with slime and appear as bacterial rods, which may then change to the characteristic branched or Y-shaped bacteriods and assimilate free nitrogen. There appear to be some 6 or seven different kinds of nodule organisms which can be distinguished by the agglutination test⁴ and which show characteristic discrimination between the various leguminous plants.

Hiltner (135) regards them as parasites attracted chemotactically to the root hair by root excretions, but prevented from getting too far into the plant by excess of the attracting material, which now becomes a deterrent. He grades them according to their virulence, the less virulent either being unable to enter the plant, or, if they do enter, being quickly resorbed, or only fixing little nitrogen; the more virulent, on the other hand, bring about energetic fixation. As evidence he adduces the well-known fact that infection proceeds best in plants weakened by nitrogen starvation and scarcely takes place at all in plants growing vigorously on

¹ *Science*, 1915, 41, 256 and 725, where earlier isolations by Nobbe, etc., are discussed.

² *Delaware Ag. Expt. Sta. Bull.*, 115, 1916.

³ L. Hiltner (135*a*).

⁴ M. Klimmer and R. Krüger, *Cent. Bakt. Par.*, 1914, 40, 256-265.

rich soils. The parasitism is beneficial to both parties: the plant gains nitrogen and the organism gains carbohydrates.

In its general outlines the process has been reproduced artificially. Leguminous plants can be fed with nitrogen compounds and made to grow perfectly without the organism. On the other hand, the organism can be grown on artificial media containing carbohydrates,¹ made to "pass through all its stages from swarmers to bacteroids, and to fix nitrogen."² The change to bacteroids is conditioned by the presence of carbohydrates or of small quantities of various acids, such as are known to occur in the plant (276). The fixation of nitrogen rapidly comes to a stop unless the resulting compound is removed, as in the plant. Golding has attained this end by an ingenious filtering device, and has thus succeeded in fixing considerable quantities of nitrogen. He has also shown that the reaction of the medium during actual fixation is alkaline, but changes to acid when fixation is stopped by the accumulation of nitrogen compounds. An actual loss then seems to set in (109).

The chemistry of the process is unknown; even the changes in the carbohydrates of the culture medium have not been worked out. Nitrogen fixation is known to take place in the nodule, which thus becomes richer in nitrogen than the rest of the root,³ and its final product is supposed to be a soluble protein which is passed on to the plant. Phosphates, calcium compounds, and carbon compounds, such as sugars,

¹ Harrison and Barlow (125) used maltose: other observers have used an infusion of the host plant. Neumann suggests pentosans (213).

² See also (13).

³ Stoklasa's analytical results with yellow lupines (*Landw. Jahrb.*, 1895, xxiv., 827) are:—

| | Blossom Formed. | Seed Beginning to Form. | Seed Ripe. |
|-------------------------------|-----------------|-------------------------|------------|
| Nitrogen in nodule, per cent. | 5.2 | 2.6 | 1.7 |
| „ in rest of root, per cent. | 1.6 | 1.8 | 1.4 |

Whiting (*Illinois Bull.*, 179, 1915) has discussed this question also.

organic acids, etc., and according to Olaru,¹ manganese compounds, have a marked effect in stimulating nodule formation in soil cultures.²

The amount of nitrogen fixed in this way is so large that it is easily measured on the field. When the host plant dies, or is ploughed into the ground, the nitrogen compounds speedily change into nitrates. A uniform piece of ground at Rothamsted was divided into two parts; on one a crop of clover was taken, on the other barley was grown. After the crops were removed samples of soil were taken for analysis, and then barley was grown in both plots. The analytical results were:—

| | Plot where Clover was Grown. | Plot where no Clover was Grown. |
|---|---------------------------------|------------------------------------|
| Nitrogen in crop (1873), lb. per acre . | 151.3 (in clover) | 37.3 (in barley) |
| Nitrogen left in soil after crop was removed (1873), per cent. . | 15.66 | 14.16 |
| Nitrogen in crop (1874), lb. per acre . | 69.4 (in barley) | 39.1 (in barley) |

These facts are well known to the practical man, and are utilised for increasing the nitrogen supply of cultivated soils and for reclaiming barren sands and clays (pp. 314 and 184). Leguminosæ are among our commonest plants, both wild and cultivated. Wherever they grow they lead to enrichment of the soil in organic nitrogen compounds through the operation of the nodule organisms. The difference between the action of this organism and that of azotobacter is that it gets its carbohydrates from the plant, and is, therefore, independent of soil organic matter. Thus, it operates perfectly well in the poorest soils, provided potassium salts, phosphates and calcium carbonate are present in sufficient quantity for the host plant,

¹ *Compt. Rend.*, 1915, 160, 280.

² J. K. Wilson, N.Y., Cornell, *Agric. Expt. Sta. Bull.*, 386, 1917. W. A. Albrecht, *Soil Sci.*, 1920, 9, 275, and various papers from A. L. Whiting's laboratory, Illinois. This may explain the action of farmyard manure on the clover crop. (E. J. Russell, *Journ. Ed. Agric.*, 1919, 26, 124.)

while azotobacter (except where it is associated with algæ, a case that requires further investigation) requires a supply of organic matter in the soil, and therefore works only in fairly rich soils where its effects are more difficult to measure.

Few improvements in agriculture have produced more marked effects than the extension of leguminous cropping. Where a leguminous crop has not hitherto been commonly grown it may be necessary to introduce the appropriate organism, as has been successfully done in Canada by Harrison and Barlow (126), in the United States by the Bureau of Plant Industry, and on the North German moors by Hiltner (135; see also 215 *c* and *d*). In Great Britain these inoculations have not proved useful, and they have never come into farming practice: the high hopes sometimes entertained that the whole problem of nitrogenous manuring—the most costly item in the farmer's fertiliser bill—might reduce itself solely to bacterial inoculation have never been realised.

Other Nitrogen Fixing Organisms.—Other organisms have been described which have the power of fixing gaseous nitrogen: among them Phoma, which in culture solutions proved about half as effective as azotobacter¹; this organism belongs to the mycorrhiza group and may play a part in plant nutrition.

Denitrification.

If the air supply of the soil is cut off by water-logging, or in the laboratory by means of an air-pump, the nitrates rapidly disappear, whilst nitrites, ammonia, or gaseous nitrogen are formed. The conditions can be so arranged that the decomposition of nitrate-bouillon by soil shall give rise to notable quantities of gaseous nitrogen, nitrous oxide (18), or nitric oxide (168 and 277*b*).

The reduction of nitrates to nitrite has long been known. As early as 1867 Schönbein² stated that it could be brought

¹ B. M. Duggar and Davis, *Annals Missouri Botanical Gardens*, 1916, 3, 413-437.

² C. F. Schönbein, *Beiträge zur Physiologischen Chemie, Zeitsch. f. Biologie*, 1867, 3, 325-340.

about by "frische Conferven, wie sie so häufig in stehendem Wasser vorkommen"; after 10 to 15 minutes' boiling, however, the property was lost. Meusel in 1875 (198) showed that it was bacterial, and could be stopped by antiseptics. The property appears to be generally possessed by bacteria and was shown by no fewer than 85 out of 109 kinds investigated by Maassen (184).

The formation of gaseous products is effected by a smaller but still considerable number of organisms; these were first investigated by Gayon and Dupetit (103), and by Déhérein and Maquenne (81*a*).

The physiological significance of the reduction appears to be that nitrates can supply oxygen to the organisms when free oxygen is no longer obtainable. It is not simply a reaction between the organism and the nitrate: easily oxidisable organic matter must be present at the same time. The partially decomposed organic matter of the soil—the "humus"—does not seem to be very serviceable (274).

There is a very sharp contrast between the bacterial production and the bacterial destruction of nitrates. Nitrate production is the work of one organism only at each stage, and the end result is a single product quantitatively equivalent to the original ammonia; no single chemical process oxidises ammonia in this complete manner. The bacterial reduction of nitrates, on the other hand, gives no single product, but a number of products not in any simple ratio, whilst the chemical reduction can readily be made to go quantitatively to ammonia.

Whether denitrification goes on to any extent in properly drained agricultural soils is doubtful, because the three essential conditions, lack of air, presence of much easily decomposable organic matter and of nitrate are rarely obtained. In 1895 Wagner and Maercker startled the agricultural world by announcing that unrotted dung destroys the nitrates in the soil and reduces the crop yield (291). Their experiments were criticised by Warrington (297) who pointed out that their dressings of dung were enormous and their results would not apply to ordinary farm practice. But it may well occur in rich soils

and it goes on to a marked extent in wet soils. Nagaoka (211, see also 74a) has shown that nitrate of soda frequently depresses, instead of increasing, the yield of rice, *sagittaria* and *juncus* on the swamp soils of Japan, an action which he attributes to the formation of poisonous nitrites. Organic manures or sulphate of ammonia are always used on such soils. Kelley has obtained similar results in Hawaii.¹

Denitrification will also take place in peaty soils, and this has led to a very interesting observation as to the effect of lime. So long as these soils are left in their natural acid state nitrification cannot take place and therefore there is no denitrification. But as soon as lime is added in sufficient quantities to give a neutral reaction nitrification begins: part of the nitrate is then reduced to nitrite by microbic activity, then a chemical reaction sets in between the nitrite and the peat whereby some nitrogen is lost and some transformed into insoluble compounds. Thus large doses of lime may produce injurious effects on peat soils (Arnd (6)).

Assimilation of Ammonia and Nitrates by Bacteria and other Micro-organisms.

Probably most of the bacteria and moulds occurring in soil are capable under suitable conditions of assimilating ammonia. The process has not been observed in ordinary arable soils rather poor in organic matter; Schlösing *père* (245c) recovered as nitrate 98 per cent. of the added ammonium compounds, so also did Russell and Hutchinson. In peaty soils, however, the assimilation of added ammonia appears to be more pronounced, amounting to nearly 30 per cent. in Lemmermann's experiments (170).

Certain organisms are capable of taking up nitrates: there is evidence (p. 179) that the action normally occurs in soils. *Algæ* would be expected to behave in this way, and certain bacteria are known to do so in presence of easily decomposed organic matter (38) and air, in which respect the action differs

¹ *Hawaii Bull.*, No. 24.

² Observed by Bierema (38) in 1909, and much investigated subsequently.

markedly from denitrification proper; it apparently goes on when sugar is added to the soil (151c). But such assimilation does not necessarily involve any loss of nitrogen, for as the organisms die they are probably decomposed with formation of ammonia and nitrates once again.

Doryland (86) has shown that this assimilation of ammonia and nitrates depends on the amount of energy material available, and may become considerable in favourable circumstances (pp. 186, 266).

The Sulphur Cycle.

Sulphur enters into the composition of several plant constituents, and it appears to undergo a series of changes in the soil whereby it is converted into sulphate, in which form it is readily taken up once more by plants. The conditions of this change have been investigated by Brown and his co-workers (60 b and c) who call the process "sulfocation".¹

Effect of Bacteria on Soil Phosphates.

It is frequently suggested that the phosphates in the soil are made more soluble through the activity of bacteria, but there is no sufficient proof. British agriculturists in the eighteenth century recognised that bones acted better as manure after fermentation than before, but the older chemists attributed the action to the decomposition of the organic matter and consequent greater accessibility of the phosphate. More recent bacteriological investigations by Stoklasa² and by Sackett, Patten, and Brown,³ however, show that certain bacteria have the power of dissolving both bone and mineral phosphates in culture solution, but the mechanism of the process is not clear. It is uncertain whether this action goes on in the soil: direct analysis has failed to demonstrate it and the evidence from field experiments is conflicting (p. 191).

¹ See also Kappen and Quensell, *Landw. Versuchs-Stat.*, 1915, 86, and J. W. Ames and T. E. Richmond, *Soil Sci.*, 1918, 5, 311.

² Stoklasa, Duchacek, and Pitra, *Centr. Bakt. Par.*, 1900, 6, 526 and 554.

³ Sackett, Patten, and Brown, *Michigan Special Bull.*, 43, 1908.

Hartwell and Pember,¹ and Tottingham and Hoffman,² failed to find any increased solubility even when rock phosphate was composted with stable manure.³

Decomposition of Organic Compounds.

Many organic compounds suffer decomposition in the soil, including some toxic to the higher forms of life and others usually regarded as very stable. Among those readily decomposed are phenol⁴ potassium sulphocyanide, naphthalene, pyridine and vanillin⁵: apparently the decomposition is brought about in each case by micro-organisms.

Some of these toxic substances may arise during the ordinary decomposition processes in the soil,⁶ and if so it is obvious that the micro-organisms which further break them down to innocuous compounds are playing an important part in soil fertility.

Swamp and Paddy Soils.

In the East—in India, Japan, etc.—considerable quantities of rice are grown on swamp soils, and the biochemical changes differ considerably from those in normal soils.

As already pointed out, nitrification does not go on but the converse process, denitrification, occurs, so that if nitrogenous artificial manures are to be used nitrates are out of the question and organic manures and ammonium salts only are possible (p. 210).

¹ Hartwell and Pember, *Rhode Island Bull.*, 151, 1912.

² Tottingham and Hoffman, *Wisconsin Research Bull.*, 29, 1913.

³ For a summary of the recent work see *Soil Sci.*, 1919, 7, 141. Solution of the phosphate proceeded when sulphur was added (J. C. Lipman and McLean, *Soil Sci.*, 1918, 5, 243 and 533; also O. M. Shedd, *Journ. Ag. Res.*, 1919, 18, 329).

⁴ N. Sen Gupta, *Journ. Ag. Science*, 1921, 11. For the organisms see G. J. Fowler, Arden, and Lockett, *Proc. Roy. Soc.*, 1911, 83, 149-156, and Wagner, *Bied. Zentr. Agrik. Chem.*, 1915, 44, 212.

⁵ W. J. Robbins and A. B. Massey, *Soil Sci.*, 1920, 10, 237, also *Ala. Exp. St. Bul.*, 195, 1917, and 196, 1917 (M. J. Funchess).

⁶ E.g. Liechti and Mooser (*Land. Jahrb. Schweiz*, 1906, 1) estimate that 34-83 kilo of phenol per hectare (30-74 lb. per acre) are formed during the decomposition of an ordinary dressing of liquid manure. Of benzoic acid no less than 400-500 kilos are supposed to be formed.

Green manuring is, however, commonly adopted and considerably benefits the crop: the decompositions taking place when the green crop is ploughed in have been studied by W. H. Harrison and Aiyer (126). In the body of the soil marsh gas, hydrogen, and CO_2 are evolved, as would be expected from the anaerobic decomposition of cellulose. But at the surface of the soil the change is entirely different and the gases consist of oxygen and nitrogen only. The difference was traced to a film of organisms which have the power of converting the marsh gas into CO_2 ¹ and this into oxygen. The oxygen is directly beneficial to the plant by providing for the aeration of the root. The production of oxygen was suppressed when the film was killed by adding copper sulphate: marsh gas and hydrogen then appeared at the surface.

It is only so long as the film is working that green manuring is beneficial to the crop. The plant roots must have oxygen and the film supplies it. The green manure, therefore, not only supplies ammonia, but also dissolved oxygen.

It would be interesting to have studies of the conditions obtaining in water cress-beds.

The Effect of Adding Plant Residues to the Soil.

The addition of plant residues to the soil is a normal occurrence and a recognised method of manuring land. The effects produced depend on the proportions of carbohydrate and protein present in the residues.²

If the conditions are favourable to the activity of micro-organisms the result of the addition is to cause an increase in numbers and in activity of the micro-organisms: this is shown by increases in oxygen absorption and CO_2 evolution. The increased numbers may have any of the following effects:—

¹ The biological oxidation of marsh gas has been described by Kaserer and Söhngen and by I. Giglioli and G. Masoñi (Pisa: *Chim. Agric. Stud. e. Ricerche*, 1909-14, Part 22, 76-108).

² For further discussion see H. B. Hutchinson (140e); P. E. Brown and F. E. Allison (60e); P. Felber, *Mitt. Landw. Hochschule f. Bodenkulture in Wien*, 1916, 3, 23.

1. If the material is rich in energy supply but not in nitrogen (*e.g.* carbohydrates) the organisms may assimilate nitrates or ammonia already existing in the soil and thus reduce the amounts of these substances present (p. 266). These circumstances are favourable to the nitrogen-fixing bacteria, and if the temperature is sufficiently high there may be an increase in the amount of nitrogen fixed (p. 203). The assimilation effects are temporarily harmful but the fixation is ultimately beneficial to the growing plant.

2. If the material is rich in nitrogen (*e.g.* protein), the organisms will produce considerable quantities of ammonia in obtaining their energy supplies. This effect is wholly beneficial to the plant (p. 185).

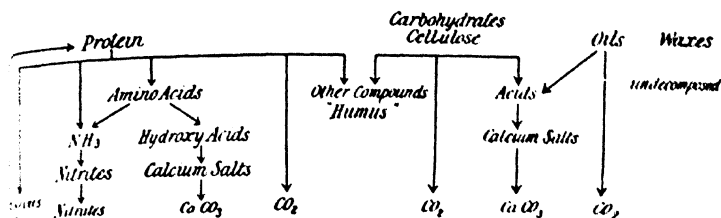
3. If the air supply is insufficient—either generally or locally—but other conditions are favourable, the organisms will obtain some of their oxygen from the nitrates present in the soil, and gaseous nitrogen will be evolved. This effect is wholly harmful to the plant (p. 208).

4. If, however, conditions are unfavourable (*e.g.* if there is acidity or too low a temperature), the organisms will not act; the material will only partly decompose and it will accumulate as peat (p. 133).

Summary of the Changes Taking Place and the Agencies Involved.

It is unfortunate that no synthesis of a soil has yet been effected, and consequently the preceding analysis of the changes taking place cannot be tested by reconstructing the whole process out of its constituent parts. On the whole the evidence is satisfactory as to the general course of the changes, but insufficient for sorting them out quantitatively and precisely. The following scheme summarises them as completely as is possible at present:—¹

¹ It will be noticed that these processes show certain resemblances to those of sewage purification beds, as worked out by Adeney (2) and Fowler (*Bacteriological and Enzyme Chemistry*, London, 1911). The decomposition in the septic tank, however, and especially in the percolating filter and the contact bed, ap-



There is good reason to suppose that all of these changes are effected by micro-organisms, but the evidence is by no means conclusive. The obvious test of working with sterilised soil is out of the question, because soil can only be sterilised by drastic methods that wholly change its character. The fact that antiseptics put an end to most of the reactions always used to be regarded as sufficient proof of their biological nature, but this argument has lost much of its force since Bredig and others¹ have shown that indisputably dead materials like spongy platinum partially lose their power of bringing about chemical changes when treated with antiseptics. Now the soil is a spongy mass, measurably radio-active (p. 89), containing numerous colloidal bodies conceivably capable of acting as catalysts, and it is possible to imagine a series of catalysts that would bring about all the known changes and be put out of action by antiseptics. Hypotheses of this nature have indeed been put forward from time to time and reactions have been discovered which cannot be attributed to micro-organisms. Cowie has shown² that the first stage of the decomposition of cyanamide in the soil, the formation of urea, is not due to organisms, but to some mineral constituent.³

pears extremely rapid to the agricultural chemist; changes such as nitrification, for which he is accustomed to allow days or even weeks, being brought about in two or three hours even at the low temperature.

For the decomposition of fats, see O. Rahn, *Centr. Bak. Par.*, Abt. II., 1906, 15, 52-61: 422-429.

¹ Cf. Bredig and Ikeda, *Zeit. Physikal. Chem.*, 1901, xxxvii., 1-68.

² *Journ. Agric. Sci.*, 1920, 10: see also Löhnis, *Zeitsch. f. Garungsphysiol.*, 1914, 5, 16-25.

³ For a study of solid catalysts see E. F. Armstrong and Hilditch, *Proc. Roy. Soc.*, 1919, 96 A, 137.

Soil rapidly decomposes hydrogen peroxide. Some decomposition of protein and of phenol and hydrolysis of cane sugar also occurs under conditions where living organisms seem excluded. There is some evidence that soil can bring about most of the chemical actions that a large number of organisms can effect, such as ammonification, but not changes peculiar to one or two organisms only like nitrification and nitrogen fixation. Sestini,¹ indeed, supposed that ammonia is oxidised catalytically by the ferric oxide always present to nitrites and nitrates, while Loew (1804) states that nitrogen can be catalytically "fixed" and converted into nitrates; Russell and Smith,² however, failed to reproduce these changes catalytically. Indeed, the chief argument in favour of the bacterial hypothesis is that all known soil processes can be reproduced in the laboratory by soil bacteria acting under conditions comparable with those known to obtain in nature, whilst they have not been produced by catalysts. The biological hypothesis, therefore, remains the simplest and most satisfying, but there is room for more evidence before it can be regarded as positively established.³

It is certain that living bacteria occur in the soil in addition to those present as spores. Some idea of the relative proportions of these two forms was obtained by making gelatin plate cultures of soil before and after treatment with toluene, which destroys living forms but not spores, or at any rate not all spores (Table LVI.). Spores form only about 25 to 30 per cent. of the total numbers, and for some unknown reason do not accumulate. Conn (see p. 187) does not consider, however, that they represent organisms of importance in the soil. The bacterial numbers are seen to be very high, but even these figures do not represent the true totals, and no medium has yet been devised that allows of the growth of all the organisms known to occur in the soil.

¹ *Landw. Versuchs-Stat.*, 1904, **60**, 103-112.

² *Journ. Ag. Sci.*, 1905, **1**, 444-453.

³ For a recent discussion see *The Proof of Microbial Agency in the Chemical Transformation of Soil* (H. J. Conn, *Science*, 1917, **46**, 252).

TABLE LVI.—NUMBERS OF ACTIVE BACTERIA AND SPORES OCCURRING IN SOILS AND CAPABLE OF GROWTH ON GELATIN PLATES. RUSSELL AND HUTCHINSON (241c). MILLIONS PER GRAM OF DRY SOIL.

| | Arable Soil. | Rich Green-house Soils. |
|---|--------------|-------------------------|
| Forms killed by toluene (<i>i.e.</i> active forms) | 7.4 | 39.6 |
| Spores surviving toluene | 2.9 | 13.3 |
| Total growing on gelatin | 10.3 | 52.9 |

The active forms must be held responsible for some at least of the oxygen absorption, carbon dioxide evolution and decomposition going on. Under comparable soil conditions a distinct relationship exists between the productiveness of the soil and the amount of bacterial activity, although it cannot be expressed in any definite form. Counts of the numbers of bacteria by any particular method fail to give results sharply connected with productiveness (although there is a general relationship) because the organisms are of the most varied description (111), and of widely different efficiency as food makers. Nor, on the other hand, have the methods of physiological grouping helped much, since they necessitate growth in culture media wholly different from the soil under temperature and water conditions that never obtain in nature. Not until the fundamental difficulty has been overcome of synthesising a soil identical with natural soil will it be possible fully to interpret the many interesting observations that soil bacteriologists are now accumulating. The subject is further discussed in Chap. VII.

CHAPTER VI.

THE BIOLOGICAL CONDITIONS IN THE SOIL.

IT is now necessary to study the soil conditions that determine the growth not only of plants but also of the micro-organisms that, as we have seen, make new plant food out of old plant residues, and render possible the continuance of vegetable life on the earth. These conditions are water supply, air supply, temperature, food supply, and absence of injurious factors.

The Water Supply of the Soil.

The water content of the soil is the difference between the amount supplied and the amount lost. The supply may come from rain, from irrigation, and from the subsoil: the loss is by evaporation or drainage from the soil or transpiration through the plant. The broad general facts are that a soil tends to maintain its water supply within fairly definite seasonal limits, any excess draining rapidly away (unless there is some mechanical hindrance), and any deficiency below the lower limit setting in only slowly. This is well shown in the curves of Fig. 17 (p. 131), where the winter level is never greatly exceeded and the summer level is fairly well maintained. The fluctuations, however, are of great importance.

The moisture range depends on the structure of the soil. The balance retained in the soil is obviously determined by the resistance the soil can offer to the forces involved in drainage or evaporation, which depends on its composition, its texture and its colloidal matter. To a considerable degree evaporation can be controlled by cultivation: this forms the basis of the so-called Dry Farming.¹

¹ See *British Ass. Repts.*, 1914, p. 645.

The main facts in regard to water supply are as follows:—

1. A sandy soil is liable to great fluctuations in moisture content, easily becoming very wet or nearly dry. Movement from underground sources of supply is rapid, but except where it is gravitational, *i.e.* due to seepage from higher ground, it does not appear to extend far. A chalk soil behaves similarly. The fluctuations are reduced and the tendency to become dry is considerably lowered when organic matter or clay is added to the sand.

2. A heavy clay soil fluctuates proportionately much less in water content, and its maximum and minimum contents are both high. Water travels only very slowly: it is common to see the soil of a field cracking with drought almost up to the edge of a stream.

3. Peat soils like clay soils have a high maximum and a high minimum water content. They show in an exaggerated degree a tendency seen in all soils—a difficulty in becoming remoistened after the soil has become dry.

These relationships are well shown in Table LVII.

TABLE LVII.—MOISTURE CONTENT¹ OF SANDY, LOAMY, AND CLAY SOILS AT WOBURN, LYING NOT FAR APART, AND UNDER APPROXIMATELY EQUAL RAINFALL CONDITIONS. RUSSELL.

| | Sandy Soil (Clay = 5.0 per Cent.). | Loamy Soil (Clay = 9.3 per Cent.). | Clay Soil (Clay = 43.0 per Cent.) |
|----------------------------|--|--|---|
| Highest observed . . . | 14.0 | 16.5 | 35.0 |
| Lowest observed . . . | 1.1 | 6.0 | 15.8 |
| Mean of all observations . | 9.0 | 12.0 | 27.0 |

For biological purposes a better idea of the meaning of these results is obtained by translating them into volumes. The soil is a porous mass and a large part of it is not occupied by solid matter at all but by air and water. Comparison of the specific gravity of the soil particles determined by the specific gravity bottle—the so-called “true specific gravity”—

¹ This determination is made by drying at 40° C.

with the specific gravity of the mass—called the apparent density—obtained by weighing a block of soil of which the volume *in situ* is known, shows that the solid matter forms 50 to 65 per cent., leaving 50 to 35 per cent. of pore space. Organic matter increases the pore space in consequence of its “lightening” action (p. 130). This is shown in Table LVIII.

TABLE LVIII.¹—PORE SPACE, WATER CONTENT, AND AIR CONTENT OF CERTAIN SOILS. RUSSELL.

| | Specific Gravity of Dry Soil. | | Volume Occupied in Natural State by | | Volume of Water. | | Volume of Air. | |
|---|-------------------------------|-------|-------------------------------------|-----------------------------|------------------------|---------------------------------------|------------------------|--------------------------|
| | Apparent. | True. | Solid Matter. | Air and Water (Pore Space). | In Normal Moist State. | After Period of Drought. ¹ | In Normal Moist State. | After Period of Drought. |
| Poor heavy loam (Rothamsted), loss on ignition, 4.3 per cent. | 1.57 | 2.36 | 65.9 | 34.1 | 23.2 | 17.0 | 10.9 | 17.1 |
| Heavily dunged arable soil (Rothamsted), loss on ignition, 10.0 per cent. | 1.46 | 2.31 | 61.8 | 38.2 | 30.3 | 20.0 | 7.9 | 18.2 |
| Pasture soil, loss on ignition, 13.0 per cent. | 1.17 | 2.22 | 52.7 | 47.3 | 40.0 | 22.3 | 7.3 | 25.0 |

In attempting to elucidate the phenomena of the water supply of the soil the most significant fact is that the soil has a certain, but not an indefinite, capacity for holding water. Two consequences follow. The plant is never able to obtain all the water present; it wilts and dies when it has taken all that its root cells can absorb, in spite of the fact that some water is left behind in the soil. At the other extreme, a soil is not able to hold more than a certain amount of water against the force of gravity, and any excess rapidly drains away. It does not appear that water once passed into the

¹ Driest periods of 1909 and 1910. During the abnormal drought of 1911 the numbers fell to 6 and 8 for the first two soils.

subsoil ever comes back again sufficiently quickly to be an important factor in plant growth.¹

The facts have been studied by two sets of investigators. Plant physiologists and ecologists have divided up the water into three kinds :—

1. The unavailable or useless water, being all below a certain minimum amount which the plant cannot absorb ;
2. The available water, being the portion absorbable by the plant, but not including the excess water ;
3. The excess water, being the amount which causes water-logging of the soil and exclusion of air, with consequent injury to the plant.

The unavailable water is marked off from the available supply by the point at which wilting just begins.² The percentage of moisture in the soil at this point, calculated on the dry weight, is called the wilting coefficient : it has been investigated by Heinrich (129) and by Briggs (55*b*, *c*). The experimental method consists in growing plants in large pots of soil, which is protected from evaporation and not supplied with water ; then when the plants wilt and die, determining the amount of water left in the soil.

It must be admitted that the wilting point is not a definite constant. For any given soil and plant it varies in a regular and predictable way with the evaporating power of the air :³ wilting occurs as soon as the rate of loss of water by transpiration from the leaves exceeds the rate of entry through the roots. The loss is determined by atmospheric conditions and the entry by resistance of the soil to the passage of water : the wilting coefficient, therefore, includes not only the water which is too firmly held by the soil to pass into the

¹ For a review of the literature see F. J. Alway and G. R. McDole, *Journ. Agric. Research*, 1917, 9, 27 ; and for a calculation of the theoretical maximum height of rise see B. A. Keen, *Journ. Agric. Sci.*, 1919, 9, 396. Leather (167*a*) obtained but little evidence of movement at Pusa.

² *I.e.* permanent wilting, when the leaves do not recover, even in a saturated atmosphere, without the addition of water to the soil.

³ J. S. Caldwell, *The Relation of Environment Conditions to the Phenomenon of Permanent Wilting* (*Physiol. Res.*, 1913, 1, 1-36).

plant, but also the water which would enter the roots if only it could move quickly enough. Shull has shown by a method described later that the water at the wilting coefficient is held by the soil with a force of about 4 atmospheres only, while the pull exerted by the plant root is approximately equal to its osmotic pressure, which, according to Hannig's¹ measurements, is about 7 or 8 atmospheres, and according to Dixon and Atkins it may exceed 20 atmospheres.²

Other investigators adopt more rapid methods. W. B. Crump (72) assumes that water left in soil air-dried at 15° C. is unavailable: he deducts this from the total moisture lost on drying at 100° C. in order to obtain the available water. This method is open to criticism in that air drying at 15° C. is a very indefinite process, and that water left in the soil at 15° may, as Shull has shown for water at the wilting coefficient, be obtainable by the plant.

Much less work has been done on the available water. Crump in studying peat soils, found large variations in the total water content of different layers, although the root development failed to indicate any corresponding difference.

But when instead of taking total water he took $\frac{\text{water}}{\text{humus}}$ ³ he obtained a much less variable result: he therefore assumed that it is not the total water which must be regarded as free, but the water per unit weight of humus:—

Soil No. 13 (September 1905) *Vaccinium myrtillus* and *Deschampsia flexuosa*, growing in a shallow hollow on a Calluna Moor, Yorks:—

¹ E. Hannig, *Ber. Deut. bot. Gesell.*, 1912, 30, 194-204.

² *Proc. Roy. Dublin Soc.*, 1912, 13, 229. Some of their results are: Roots of *Beta vulgaris*, up to 21.18 atmos.; of *Ilex aquifolium*, 7.64 to 10.38 atmos.; of *Helianthus tuberosus*, 12.76 to 18.67 atmos.

³ The water being weight when sampled minus weight after drying at 15°: and the humus being loss on ignition of oven-dry soil.

| | Air dry Peat. Water at 15° C. Per Cent. | Humus. Per Cent. | Water Humus' Per Cent. |
|---|---|---------------------|------------------------------|
| I. Loose fibrous peat $\frac{1}{4}$ to $\frac{3}{4}$ inch . | 176.4 | 77.8 | 2.23 |
| II. Compact peat $\frac{1}{4}$ to $\frac{3}{4}$ inch . . . | 61.0 | 17.4 | 3.52 |
| III. Sandy "sub-peat" 1 to 2 inches | 21.1 | 8.1 | 2.59 |

Rootlets penetrated II. and entered III.

No similar studies of agricultural soils seem to have been made.

Soil physicists, on the other hand, have divided the soil water under the following headings:—

1. Hygroscopic moisture, being the moisture that a dry soil can absorb from a moist atmosphere.

2. Capillary water, being water held by capillary or surface forces which, being much stronger than gravity, prevent it being lost by drainage.

3. Gravitational water, being the excess water which is capable of draining away.

The hygroscopic moisture is marked off from the capillary water by the point called the *hygroscopic coefficient*, the percentage of moisture in a soil which, initially dry, has been placed in a saturated atmosphere and absorbed water till it is in equilibrium therewith (Hilgard (133a); Alway (3b)). In most soils this falls between 14 and 3.

The upper limit for the capillary water is determined by allowing a column of soil saturated with water to stand in a cylinder with a perforated base till all drainage has ceased, the soil being meanwhile protected from evaporation (Hilgard (133a)). The percentage of water finally retained is called the *water-holding capacity* under the conditions of the experiment. It is difficult to determine exactly, but it usually varies between 15 and 40.

These distinctions were drawn up in the first instance when soil was supposed to have a sand grain structure and when considerable importance was attached to the capillary films surrounding the particles. Some modification seems

desirable now that the soil is recognised to possess marked colloidal properties. The modification is rather in the conception than in the grouping, but it is important because of the necessity for clear ideas on the subject.

We start from the fact recognised by Briggs and Shull, and demonstrated by Keen (146*a, b*) that the state of the water in the soil is the same whether we are considering the first per cent. or the last: there is no break over the whole range of moisture content from dryness to saturation.

It follows, therefore, that such divisions as the foregoing must indicate changes in the force by which the water is retained, not changes in the water itself. Broadly speaking, there are three types of forces which come into play:—

1. Intimate surface forces of very high magnitude (*e.g.* 1000 atmospheres or more) which, however, are capable of acting effectively only on a small amount of water;
2. The ordinary surface forces commonly spoken of as capillarity, capable of acting on considerably more, but not on an indefinite amount of water;
3. Gravity, which acts on all the water independent of its amount.

All these forces act, but the relative importance and effectiveness of each depends on the amount of water present. While no sharp points of demarcation exist there are, for any soil, percentages of moisture for which one force exerts a predominating effect.

The first attempt to divide soil water on the basis of the forces retaining it was made by Briggs and Shantz in 1912 (55*c*): a powerful centrifuge was employed which threw out all water held by forces of less than 1000 times that of gravity, which is equivalent to about one atmosphere. The percentage of water held at this point is called the *moisture equivalent*.

A considerable advance was made by Shull (264). He used the attractive pull by seeds as a means of estimating the force with which water was held by the soil, and he calculated the pull of the seeds by studying their absorption of water

vapour from solutions of known osmotic pressure and their absorption of water vapour when suspended over dilute solutions of sulphuric acid. Fig. 22 shows the force with which the water is held in a heavy loam where the wilting coefficient is high: between 80 per cent. and 20 per cent. of moisture the hold is but slight, then it increases rapidly and continuously till at 5 per cent. of moisture it amounts to 1000 atmospheres. But there was no break at the wilting coefficient

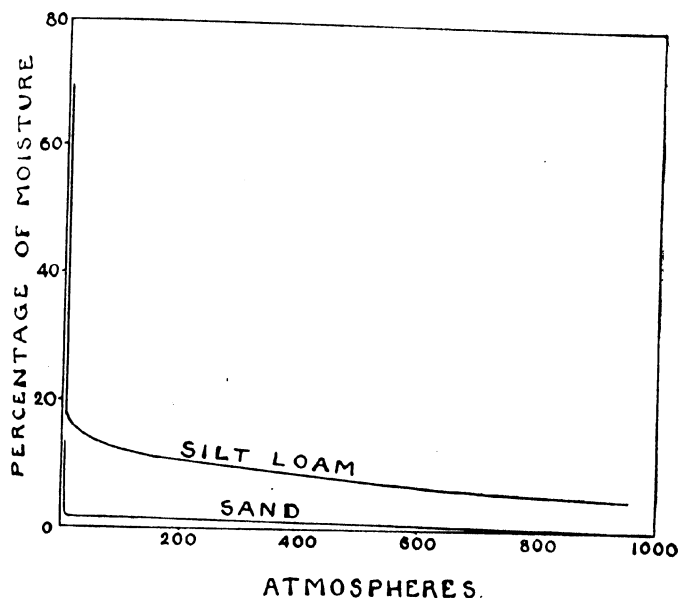


FIG. 22.—Magnitude of force with which water is held by soil, showing change with decreasing water content. (C. A. Shull, 264.)

(4 atmospheres): indeed, seeds absorbed nearly as much water from soil at this point as they did from pure water.

With sand the hold is slight almost all the way: only near the end does it become great.

Bouyoucos (49c) has made a division by a somewhat different method. He measured the depression of the freezing-point of the soil water as the soil became successively dryer and drew the qualitative conclusion that in soil some of the

water was "*unfree*" in the sense that it took no part in the process. Keen has shown (146*c*) that Bouyoucos' figures are capable of quantitative interpretation, the amount of "*unfree water*" at any total moisture content being a function of the amounts of "*free*" and total water.

These various divisions do not correspond with one another. Briggs and Shantz (55*c*) have worked out the relationships between some of them. They find that the hygroscopic coefficient is on the average about 0.68 times the wilting coefficient. Alway, on the other hand (3*b*), finds that the wilting coefficient and the hygroscopic coefficient are approximately equal.

Further, Briggs and Shantz (55*c*) have shown that the following relationship exists between the hygroscopic coefficient and the composition of the soil:—

Hygroscopic coefficient = 0.007 sand + 0.082 silt + 0.39 clay, where sand, silt, and clay are expressed in American units.

Alway (3*a*) has modified the formula to make it fit the semi-arid or transition soils of Nebraska:—

Hygroscopic coefficient = 0.005 coarser fractions + 0.07 very fine sand + 0.082 silt + 0.39 clay.

Briggs' "moisture equivalent" is rather different and is about 1.8 times the hygroscopic coefficient. Briggs and Shantz in their paper show its relationship to the other quantities.

General agricultural experience shows that the excess water of the plant physiologist is approximately the same as the gravitational water of the physicist.

The fact that these divisions do not exactly correspond is a strong argument against the reality of their existence. It is inconceivable that water could exist in a dozen different states in the soil. Briggs and Shull both regarded the condition of the water as continuous, and Keen has afforded rigid proof that this is the case. In the course of its range from 0 to 20 or 40 per cent. by weight of the soil the water is held by forces varying in magnitude from 1000 atmospheres or more down

to a fraction of an atmosphere, and finally so weak that gravity easily overcomes them. Over such a wide range it is convenient for the investigator to make divisions, and he is quite at liberty to do this so long as he realises that his divisions are arbitrary and not real. The various coefficients referred to in the preceding pages have their uses, but they become dangerous when they are taken to imply a break or an abrupt change in the condition of the water. There appears to be neither break nor division in the state of the soil water.

Air Supply.

The figures given in Table LVIII. show that about 10 per cent. of the volume of a normally moist soil is occupied by air, but this volume is perpetually varying inversely as the amount of water varies. These changes alone would lead to

TABLE LIX.—COMPOSITION OF THE AIR OF SOILS, PER CENT. BY VOLUME.

| Soil. | Usual Composition. | | Extreme Limits Observed. | | Analyst. |
|--|--------------------------------------|---------------------------------|---|--|---|
| | Oxygen. | Carbon-dioxide. | Oxygen. | Carbon-dioxide. | |
| Arable, no dung for 12 months | 19.20 | 0.9 | — | — | Boussingault and Lévy (48a). |
| Pasture land | 18.20 | 5.1.5 | 10.20 | 5.11.5 | Schloesing fils (246). |
| Arable, { sandy soil uncropped, { loam soil no manure, { moor soil Sandy soil, dunged and cropped (potatoes), 15 cm. Seradella, 15 cm. | 20.6 20.6 20.0 20.3 20.7 | .16 .23 .65 .61 .18 | 20.4-20.8 20.0-20.9 19.2-20.5 19.8-21.0 20.4-20.9 | .05-.30 .07-.55 .28-1.40 .09-.94 .12-.38 | Lau (159) mean of determinations made frequently during a period of 12 months. Values at depths of 15 cm., 30 cm., and 60 cm. not widely different. (30 cm. values given here.) |
| Arable land unmanured | 20.4 | 0.2 | 18.0-22.3 | 0.01-1.4 | Russell and Appleyard (241g). |
| " " dunged | 20.3 | 0.4 | 15.7-21.2 | 0.03-3.2 | |
| Grass land | 18.4 | 1.6 | 16.7-20.5 | 0.3-3.3 | |

(Atmospheric air contains 21 per cent. of oxygen and .03 per cent. of CO₂.)

a renewal of the air supply in the soil, but other factors, diffusion, changes in pressure, air movements, etc., come in, making the gaseous interchange still more complete. At soil depths reached by plant roots—some 6 to 12 inches—the soil air presents no abnormal features: there is some accumulation of carbon dioxide, because this gas diffuses out more slowly than water vapour, oxygen, or nitrogen, but the percentage volumes of oxygen and nitrogen are nearly the same as those of the atmosphere. Of course, if the air supply is cut off by an accumulation of water on the surface, the oxygen may fall considerably in volume, but this case is exceptional in England on cultivated land. At still lower depths the volume of carbon dioxide may rise above 1 per cent.¹

As might be expected, the carbon dioxide is higher in amount in summer than in winter, and higher in grass land than in arable. It may rise considerably in grass land, or in land recently dunged.

Russell and Appleyard (241g) obtained evidence of a dissolved atmosphere in soil, composed mainly of CO₂ with some nitrogen. E. H. Richards has shown² that rain brings down an appreciable amount of dissolved oxygen:—

DISSOLVED OXYGEN BROUGHT DOWN IN RAIN. RICHARDS.

| | Average Rainfall (Inches) at Rothamsted (28 Years). | Dissolved Oxygen. | |
|--------------|---|-----------------------|------------------|
| | | Parts Per Million. | Lb. Per Acre. |
| Summer . . . | 13'32 | 9'0 | 27'12 |
| Winter . . . | 15'50 | 11'2 | 39'27 |
| Year . . . | 28'82 | — | 66'39 |

Leather has obtained much higher CO₂ and lower oxygen values in India under monsoon conditions when the soil is virtually water-logged and at high temperature; in land

¹ Pettenkofer's determinations at Munich at depths 1½-4 m. below the surface are published in *N. Rep. Pharm.*, 1873, xxi., 677-702, and abstracted in *Journ. Chem. Soc.*, 1873, 361, and 1874, 36.

² *Journ. Ag. Sci.*, 1917, 8, 331-337.

carrying *Sanai* (*Crotalaria juncea*) and other crops during the monsoon the CO_2 rose to 16 to 20 per cent. and the oxygen fell to 2 to 4 per cent. only.¹

The Temperature of the Soil.

The temperature of the surface layer of soil, which in turn determines the temperature of the lower layers, is the resultant of several different effects. The actual amount of heat reaching the surface is that portion of the sun's rays that passes unabsorbed through the atmosphere, and is therefore dependent on the climate. The intensity of distribution of the heat over the surface depends on the slope of the land, and is greater the more nearly the land lies at right angles to the mid-day rays: thus, in our latitudes a south slope is warmer than a north slope, so much as often to produce marked vegetation differences. Many of the rays may be intercepted by vegetation, consequently land densely covered by plants is cooler and moister than bare land; advantage is often taken of this fact in tropical countries to protect soil from intense evaporation by the growth of "shade" crops. Of the rays that do finally reach the surface not all are absorbed, an unknown fraction being reflected back again into space: although no actual measurements have been made, the loss from this cause is probably greater on a white chalky soil than on a black humus soil.

The extent to which a given quantity of absorbed heat raises the temperature of a soil depends on its specific heat and this again on its water content. Dry soil has a specific heat of 0.2, while wet soil has a specific heat approximating more closely to 1, hence under equal sunshine conditions a dry soil will attain a higher temperature than a moist one. Not infrequently the surface layer of the soil is hotter than the air, especially on a sunny day.²

¹ J. W. Leather, *Pusa Chem. Memoirs*, 1914, 4, 85-134. The effect on germination is discussed by A. Howard in *Ag. Journ.*, India, 1915, 10, 106.

² This is especially the case in hot climates. Leather (*Pusa Chem. Memoirs*, 1914, 4, 1-49) states that the maximum temperature at Pusa (India) is 20° C. above the maximum air temperature in the shade.

The temperature of the body of the soil depends on two factors—the specific heat of the various layers of soil, and the rate of propagation of the heat wave. At Rothamsted the maximum temperature is commonly attained about 2.15 p.m. in the air, but at 5.30 p.m. at 6 inches depth in the soil. The ease of propagation is not constant, *e.g.* it is much increased by an increase in moisture content. This, however, much increases the specific heat; and the result of the two factors is a considerable damping of the temperature wave as it progresses through the soil. In consequence, fluctuations in air temperature of less than 2° C. are often inappreciable at 6 inches depth.

The temperature curve of the soil at a depth of 6 inches below the surface somewhat resembles that of the air in summer, but it lacks the sharp peaks and depressions. The soil minimum is always greater than that of the air, especially in summer; the maximum is also usually greater in winter, although it is sometimes below in summer. In winter time, however, the curve is often flat all the twenty-four hours and sometimes shows practically no variation for two or three days together (146*d*, Fig. 23).

As a result of the interaction of these factors marked temperature variations occur over comparatively small areas of soil, being produced by differences in aspect, moistness, vegetation cover, looseness, and so on. Illustrations are afforded in Table L*X*.

For ordinary working purposes the following summary will be found useful:—

- (1) A south slope is warmer than a north slope.
- (2) Bare land is warmer than land covered with vegetation, excepting during winter months.
- (3) Soil exposed to the sun's rays is often hotter than the air, and is subject to considerable temperature variations, which, however, only slowly affect layers three or more inches deep.
- (4) Moist soil, being a better conductor than dry soil, is much more uniform in temperature.

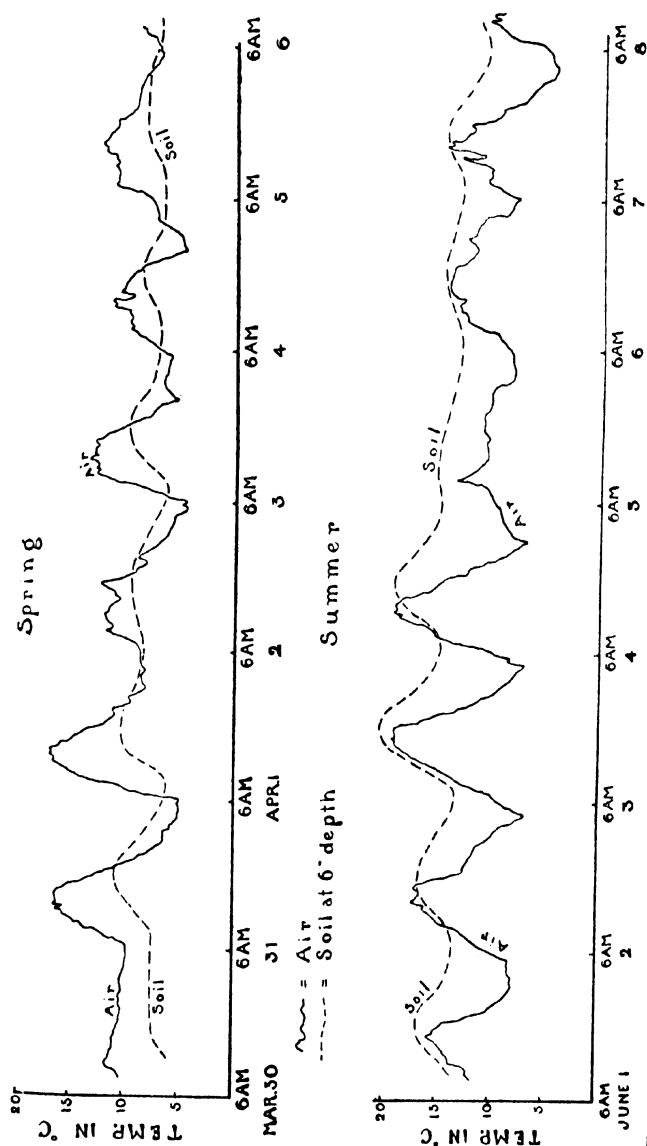


FIG. 23.—Soil temperatures in spring and summer taken by a continuous recording thermometer embedded 6 inches in bare ground at Rothamsted. (Keen and Russell, 1964.)

(5) The top 6 inches of soil has a higher mean temperature than the air both in summer and in winter. At 6 inches the warmer part of the day centres round 5.30 p.m., and the cooler part round 9.30 a.m.

(6) The warming of the soil in spring is facilitated by drying; the cooling in autumn is increased by clear nights and diminished by rain (*Keen and Russell, 146d.*) /

TABLE LX.—TEMPERATURES OF SOIL AT DIFFERENT DEPTHS UNDER VARYING CONDITIONS. RUSSELL.

Effect of Weather.

| | Air Temp. | Temperature of Bare Soil. | | | | | |
|----------------------------------|-----------|---------------------------|---------------|---------------|-------------------------|---------------|---------------|
| | | Untouched. | | | Surface Stirred by Hoes | | |
| Hot sunny day, 20th June, 1910 | 30° | ½ inch. 35° | 3 inch. 30.5° | 6 inch. 27° | ½ inch. 31.5° | 3 inch. 29.8° | 6 inch. 26.5° |
| Cold cloudy day, 27th June, 1910 | 18° | ½ inch. 17.5° | 3 inch. 16.7° | 6 inch. 15.8° | ½ inch. 17° | 3 inch. 16.3° | 6 inch. 15.5° |

Effect of Vegetation.

| | Warm Weather, 5th Oct., 1910, Air Temperature, 17° | | | Cold Weather, 4th Jan., 1911, Air Temperature, 3.5° | | |
|--|--|---------------|---------------|---|--------------|--------------|
| | ½ inch. 17° | 3 inch. 16.7° | 6 inch. 15.5° | ½ inch. 3° | 3 inch. 2.5° | 6 inch. 2.5° |
| Bare soil | | | | | | |
| Soil covered with living vegetation (grass land) | 15.5° | 15° | 14.5° | 3° | 3° | 3° |
| Soil covered with dead vegetation (mulched land) | 15.5° | 15° | 14.5° | 2.5° | 2.0° | 2.0° |

Records extending over periods of some months have been published by Wollny (318) and by Thiele (281). British data generally refer only to 6 inch or 12 inch readings; they have been collected and worked up by Mawley, by Mellish,¹ and by Franklin.² Systematic readings are taken at the Radcliffe Observatory, Oxford,³ at Kew, and also at Rothamsted, where a continuous self-recording thermometer is installed. Detailed

¹ See *Quart. Journ. Roy. Meteor. Soc.*, 1899, xxv., 238-265.

² *Proc. Roy. Soc.*, Edin., 1920, 40, 10, 56.

³ See A. A. Rambaut, *Radcliffe Observations*, 1901, 48, 1-245, and 1911, 51, 103-204; also *Phil. Trans.*, 1901, 195 A, 235-8.

records of soil temperatures at East Lansing, Mich., have been taken by Bouyoucos (49a), who has also discussed their effect on the physical properties of the soil.

Food Supply.

In spite of numerous investigations our knowledge of the plant food in the soil is very limited. On physiological grounds it is supposed that the whole of the nutrient material coming from the soil enters the plant in the dissolved state, but whether the actual soil solution is all the plant gets, as Whitney and Cameron suppose (see p. 173), or whether the carbon dioxide respired from the roots¹ effects the solution of more material than is already dissolved, has not been ascertained. The soil solution may safely be regarded as the minimum food supply, which is reinforced to an unknown extent by the soluble substances in the soil.

Nitrogen nutrition presents a tolerably simple case because plants growing on cultivated soils probably absorb all their nitrogen as nitrates, which are readily and completely dissolved by water, whilst plants in undisturbed soil—grass land, etc.—probably utilise ammonium compounds as well. Potassium and phosphorus nutrition present greater difficulties because very little is known about the compounds of these elements in the soil. This particular problem is of such technical importance that it has been necessary to do something empirically, and by common agreement the small fraction of the phosphorus and potassium compounds soluble in dilute acids is called "available" food material, while the rest is said to be

¹ At one time it was supposed that special acids were excreted by plant roots to dissolve insoluble food materials in the soil. This idea, which was a survival of the mediæval view that plants are wholly analogous to animals, persisted into our own times, but has been shown to be untenable by Czapek (*Biochemie der Pflanzen*, Bd. 2, pp. 872 et seq.). So far as is known CO_2 is the only acid excreted. The evidence is of the negative kind and is therefore not entirely satisfying, so that the problem is periodically brought up again; recently, for instance, Pfeiffer and Blanck stated that other acids also are given off (224d). Cf. (275), and footnote, p. 33. For a recent discussion, with references, see H. Kappen, *Untersuchungen an Wurzelsäften* (*Landw. Versuchs-Stat.*, 1918, 91, 1-40).

"unavailable".¹ Here, however, the agreement ends, for no two dilute acids give the same results and no two Associations of Agricultural Chemists recommend the same dilute acid. Dyer's 1 per cent. citric acid (91) is adopted in Great Britain, and its use has been justified by Wood's investigations (319) and by those of Hall and Plymen (120a).² N/200 hydrochloric acid has been recommended in the United States, 2 per cent. hydrochloric acid by Nilson in Sweden, aspartic acid in Hawaii, and so on. Mitscherlich (201c) uses a saturated solution of CO₂ as being the nearest approach to natural conditions. Some of the younger workers in the United States are using the water extract as the nearest feasible approach to the soil solution.³ A 2 per cent. citric acid solution has been suggested by Bergu.⁴ Bogdanow⁵ in his investigations of Russian soils used 2 per cent. acetic acid. The German "Verband landwirtschaftlicher Versuchsstationen" recommends both 25 per cent. and 10 per cent. hydrochloric acid (see 224f). Lastly Ramann proceeds in a different manner altogether and adopts a method depending on the interchange of bases. The results obtained by different acids are shown in Table LXI. Similar results have been obtained by Engels (95) (see also p. 344).

An empirical method can be retained only so long as it justifies itself by results. Few agricultural chemists of repute would be prepared to draw up a scheme of manuring on the basis of soil analysis alone, though probably most would like to have some analytical data before them.

Even strong hydrochloric acid dissolves only a part of the potash and phosphoric acid, the remainder not coming out till after treatment with hydrofluoric acid.

The different action of the various dilute acids has been

¹ Daubeney (78) originated this distinction, using the terms "active" and "dormant".

² Also those of O. Lemmermann, A. Einecke, and L. Fresenius in Germany (*Landw. Versuchs-Stat.*, 1916, 89, 81-195).

³ J. S. Burd (62a).

⁴ *Landw. Versuchs-Stat.*, 1901, 55, 19; also by Engels (95).

⁵ *Expt. Station Record*, 1900, 11, 130; 1901, 12, 725.

adduced as evidence of the existence in soils of a considerable number of phosphorus and potassium compounds of varying degrees of solubility, but no such assumption is necessary. It more probably represents the division of these compounds between two solvents, the weak acid and the colloidal complex in which they are present in the soil (see p. 172).

TABLE LXI.—AMOUNTS OF K_2O AND P_2O_5 EXTRACTED BY ACIDS FROM ROTHAMSTED SOILS, PER CENT. OF DRY SOIL. HALL AND PLYMEN (120a).¹

| K_2O . | Strong HCl. | Dilute Acids Equivalent to 1 per Cent. Citric Acid. | | | |
|------------------------|-------------|---|--------|--------------|----------------|
| | | Citric Acid. | HCl. | Acetic Acid. | Carbonic Acid. |
| Broadbalk, unmanured . | 0'380 | 0'0043 | 0'0147 | 0'0082 | 0'0111 |
| „ minerals only | 0'463 | 0'0458 | 0'0522 | 0'0307 | 0'0215 |
| „ dung . . | 0'453 | 0'0400 | 0'0684 | 0'0451 | 0'0380 |
| P_2O_5 . | | | | | |
| Broadbalk, unmanured . | 0'114 | 0'0080 | 0'0021 | 0'0011 | 0'0005 |
| „ minerals only | 0'228 | 0'0510 | 0'0360 | 0'0098 | 0'0058 |
| „ dung . . | 0'209 | 0'0477 | 0'0224 | 0'0166 | 0'0095 |

More definite information can be obtained about the nitrogen compounds. The amount of ammonia and of nitrate can be ascertained in any desired depth of soil. On cultivated land the amount is not generally more than enough for one year's crop, any balance being liable to be washed out in winter, so that the plant depends in spring on the activities of the decomposition processes for a regular supply of nitrogenous food. This is one of the factors that produce the marked retardation of plant growth in spring when the soil is wet and cold, especially after a wet winter when the washing-out process is complete, and it further accounts for the remarkable benefits produced by even small additions of nitrate of soda or sulphate of ammonia to the soil at this period.

In dry regions the accumulation of plant food and other soluble decomposition products in the soil may be too great to admit of plant growth, and bare patches or regions arise

¹ For other results see F. Münter, *Zur chemischen Bodenanalyse* (Landw. Versuchs-Stat., 1919, 91, 181-189).

known as "alkali soils" from the circumstance that sodium and potassium carbonates are often present. In wetter climates the soluble substances tend to be washed out more completely, but notable quantities often persist in heavy clay soils, especially where the drainage is bad, and may produce injurious effects on vegetation.

In discussions of the plant food in soils it is often assumed that the only significant plant nutrients are nitrates, phosphates, sulphates and salts of potassium, calcium, magnesium and iron, commonly called the "essential" plant foods. Perfect plants can be raised in water cultures containing only these substances. Reference to Fig. 12 (p. 68), however, shows that productiveness is not always maintained indefinitely simply by supplying these salts, and not nearly so well as when the complex farmyard manure—excreta, litter, etc.—is used. It is known also that certain other compounds besides the "essential" foods may increase plant growth (p. 56). Further, Russell and Petherbridge have shown that on heating soil to 100° something is formed that stimulates root production to a remarkable degree. Are these effects the results of nutrition or of stimulation? Are the manganese, fluorine, etc., compounds and the beneficial soil constituents indispensable nutrients of which only traces are required, or are they, as Armstrong expresses it, "condimental" foods?

It would be attractive to think that some of the vague physiological conditions that trouble the grower are to the plant what beri-beri and similar diseases are to the animal—the result of withholding some essential or useful "accessory substance". Bottomley¹ considers that certain substances obtained in the bacterial decomposition of peat are of this nature. Mazé has published some remarkable results² show-

¹ W. B. Bottomley, *Proc. Roy. Soc.*, 1914, **88**, 237-247, and 1920, B 91. 83; Florence A. Mockeridge, *Biochem. Journ.*, 1920, **14**, 432. The substances are called auximones. See also J. F. Breazeale, *Journ. Ag. Research*, 1919, **18**, 267, who found that citrus seedlings grew better in peat extract than in distilled water.

² Mazé, *Compt. Rend.*, 1915, **160**, 211.

ing that maize fails to complete its growth in water cultures containing all the recognised nutrient salts if these are chemically pure, but it grows normally as soon as tap water is introduced. No combination of added salts has as good an effect as the tap water (Table LXII.).

TABLE LXII.—GROWTH OF MAIZE IN WATER CULTURES. MAZÉ, 1915.

| | |
|--|------|
| Culture solution containing compounds of boron and aluminium (tap water) | 43 |
| " " " " " " " " (distilled water) | 24 |
| " " " " " " " " aluminium and arsenic | 16.5 |
| " " " " " " " " arsenic and iodine | 36.6 |

A considerable amount of work has obviously to be done before the problem can even be clearly stated. And against all this is the fact, abundantly demonstrated by Dr. Brenchley, that barley and peas make full growth in nutrient solutions containing only the ordinary "essential" foods (54*d*).

The Concentration of the Soil Solution.

It is well-known that plants cannot tolerate too concentrated a solution, otherwise their osmotic relationships are seriously disturbed. The cell sap of the plant root exerts an osmotic pressure of 7-20 atmospheres (p. 222). In ordinary agricultural soils the soil moisture has a concentration of the order of 0.1 to 0.2 per cent. and an osmotic pressure of about 0.2 to 1 atmospheres (p. 125). In some soils, however, the concentration and the osmotic pressure of the soil solution rise much higher, and in the alkali soils it becomes too high for plant growth. Gola (108) has proposed to classify habitats on the basis of concentration of soil solution, his groups being—over 2 per cent. ; 2 to 0.5 per cent. ; 0.5 to 0.2 per cent. ; below 0.2 per cent.¹ The scheme is interesting and promising: it would be improved by taking into account the composition of the solution which at higher concentrations is of great importance (p. 78) and by stating the limits in terms of osmotic pressures.

¹ The total concentration of spring and river waters is of the order of 0.1 to 0.3 per cent.

There has been much controversy as to the effect of concentration of the nutrient solution on plant growth. The relationship is curiously elusive: at first sight it appears a most simple thing to ascertain. The difficulty is to change the solutions sufficiently often to prevent complications due to exhaustion of essential nutrient substances.

Breazeale (51*a*) concluded from his experiments that small variations in concentration of the nutrient medium are without effect on plant growth; this view is accepted by Whitney and Cameron and in this country by Stiles.¹ It is vigorously controverted by Hall, Brenchley, and Underwood (121*c*: see also 54*c*), who maintain that within certain limits the plant growth is affected by and increases with the concentration, although recognising that the differences become less as the solutions are more frequently changed. Hoagland and Sharp (136*c*) also find that growth increases with increasing concentration up to a point, beyond which no further growth is obtained: absorption of nutrient salts still continues, however. Some of their results with barley, after two days growth, are given in Table LXIII.

TABLE LXIII.—TRANSPIRATION AND GROWTH OF BARLEY IN SOLUTIONS OF DIFFERENT CONCENTRATIONS. HOAGLAND AND SHARP, 136*c*.

| Concentration of Solution, Parts per Million. | Osmotic Pressure, Atmospheres. | Average Dry Weight of Tops, Grms. | Transpiration per gm. Dry Weight of Tops. | | Average Absorption of Electrolytes from each Jar, Parts per Million. |
|---|--------------------------------|-----------------------------------|---|----------------|--|
| | | | 1st Day, Grms. | 2nd Day, Grms. | |
| 200 | 0.10 | 0.43 | 50 | 94 | - 25 |
| 800 | 0.32 | 0.46 | 46 | 91 | 72 |
| 2500 | 0.85 | 0.50 | 34 | 64 | 288 |
| 6000 | 2.07 | 0.50 | 33 | 48 | 402 |

Adequate concentration of nutrients is of great importance in the early stages of plant growth: in later stages high concentration is less necessary and may be undesirable.²

¹ *Annals of Botany*, 1915, 29, 89.

² See also J. S. Burd, *Journ. Ag. Research*, 1919, 18, 5172.

Rate of Renewal of Plant Nutrients.

Whatever the effect of variations in concentration there is no question that the rate of renewal of the supply of plant nutrients to the roots is an important factor in soil fertility. Some of the most fertile soils in England are not particularly rich in plant nutrients, but they are able to keep the roots well supplied.

The Nature of the Medium on which the Soil Life goes on.

It is a mistake to suppose—and this point cannot be too strongly emphasised—that the medium on which the soil organisms live and which is in contact with the plant roots, is the inert mineral matter that forms the bulk of the soil. Instead, the medium is the colloidal complex of organic and inorganic compounds, usually more or less saturated with water, that envelops the mineral particles; it is, therefore, analogous to the plate of nutrient jelly used by bacteriologists, while the mineral particles serve mainly to support the medium and control the supply of air and water and, to some extent, the temperature. As yet our knowledge of the detailed composition of this medium is slight but it is steadily improving (see Chap. IV.); and we shall get a very false idea of the conditions of life in the soil unless we recognise the main fact of its existence and fundamental significance. Gola (1086) has discussed the influence of the colloidal complex in determining plant habitats, and Söhngen (269) its effect on the activities of micro-organisms.

Sourness, or Reaction of the Soil.

Many soils, including some of the most fertile, are neutral or feebly alkaline to litmus paper and contain so much basic material that interaction with dissolved salts leads only to an interchange of bases without turning the solution acid.

But other soils, including many infertile ones, are acid to

litmus paper, and so poor in basic material that on interaction with a dissolved salt they give an acid solution.

Such soils are called "sour" or "acid": the word "sour" is at present more suitable, as it is uncertain whether the effects produced on plants and micro-organisms are really due to acidity or to lack of bases (see p. 117). Whatever the cause, however, the effects are very striking. Some of the plants and organisms are very intolerant and rapidly disappear from sour soil; few can tolerate any large degree of sourness. The simplest case is seen on cultivated land where single crops are grown; experience in England and in America is set out in Table LXIV.

TABLE LXIV.—DEGREE OF TOLERANCE OF SINGLE CROPS TO SOURNESS OR ACIDITY.

| England. | | Rhode Island (Hartwell and Damon, 1286). | |
|---|--|--|--------------------------|
| Less Tolerant. | More Tolerant. | Less Tolerant. | More Tolerant. |
| White clover | Lupines ¹ | Red clover | Beans |
| Red clover | Alsike | <i>Alopecurus prat.</i> | Maize |
| Foxtail (<i>Alopecurus pratensis</i>) | Oats | Lucerne | Potatoes |
| Barley | Potatoes | <i>Poa pratensis</i> | Tomato |
| | Sweet vernal grass (<i>Anthoxanthum</i>) | <i>Dactylis glomerata</i> | <i>Agrostis canina</i> |
| | Sheep's fescue | Barley | <i>Agrostis vulgaris</i> |
| | Yorkshire fog (<i>Holcus lanatus</i>) | | |
| | Sorrel (<i>Rumex acetosa</i>) | | |
| | Rhubarb | | |

It would obviously be feasible to draw up a system of cropping suitable to sour soils containing only crops tolerant of acid conditions, and Corville² has suggested that this would often prove more economical than attempts to neutralise acidity by carrying lime from long distances.

The phenomena are very striking in natural conditions where there is a mixed flora. On the grass plots of neutral reaction at Rothamsted there are about 45 species of plants: on the somewhat acid plots there are fewer, and finally on the

¹ See p. 305.

² U.S. Dept. Agric. Bull., 6, 1913.

most acid plots there are only 7 species. Many instances are found in England on the loams overlying the chalk Downs in the southern counties, some of which are sour, while others are not. Thus on the Wiltshire Downs, the so-called "bake" land is sour, but it is surrounded by neutral or chalky soils: on it is found the Sheep's sorrel (*Rumex acetosella*), Scarlet Pimpernel (*Anagallis*), and Knawel (*Scleranthus annuus*), while the Toadflax (*Linaria vulgaris*), white and bladder campion (*Lychnis vespertina* and *Silene inflata*) are conspicuously absent, although common on the chalk in the district.¹ The influence of sourness on the wild vegetation of uncultivated land (Harpenden Common) has been studied by Hutchinson and McLennan (140d) and on woodland vegetation by E. J. Salisbury (242), in both cases the "lime requirement" was used as the measure of sourness. Their results are given in Table LXXV. Salisbury further finds *Quercus sessiliflora* on the more sour and *Q. robur* on the less sour soils. Attempts have often been made to draw up lists of plants indicating sourness, but the problem is not altogether simple. A plant may be eliminated from the natural flora not because it cannot tolerate the degree of sourness in the soil, but because it tolerates this sourness less well than its competitors. Another plant may flourish in sour soil, not because conditions of sourness are suitable to it, but because of the absence of effective competition. Thus sorrel is often described as an indicator of sourness, but this is not entirely correct: it is not the presence of sorrel that is symptomatic, for sorrel will grow quite well on chalk soils: it is rather the presence of sorrel, sweet vernal grass, etc., combined with absence of clover. The effect of sourness, like that of any other adverse factor, is to alter the balance in competition somewhat against a particular set of plants, which tend therefore to be eliminated in time. We shall find other cases (p. 301) where even a small factor can profoundly affect the natural flora if its action continues long enough.

¹ W. E. Brenchley, *Annals of Botany*, 1912, 26, 95-109.

TABLE LXV.—LIME REQUIREMENT AS RELATED TO VEGETATION.

| Harpenden Common. Hutchinson and McLennan (140d). | | Woods. Salisbury, 242. | |
|---|--|------------------------|---|
| Average Lime Requirement of Soil. | Dominant Flora. | Lime Reqt. | |
| Approx. 0.22 per cent. CaCO_3 | Wild white clover (<i>Trifolium repens</i>) | 0.24 | <i>Mercurialis</i> |
| " 0.26 " " | Fescues (<i>F. ovina</i> and <i>rubra</i>) | " | |
| " 0.31 " " | Mixed, Yarrow, wood- rush and moss | " | |
| " 0.39 " " | Gorse | " | |
| " 0.43 " " | Yorkshire fog. | 0.52 | <i>Holcus</i> , <i>Anthoxanthum</i> , <i>Cnicus</i> |
| " 0.53 " " | Sorrel | 0.62 | <i>Holcus</i> <i>Anemone</i> |

Similarly there is a close relation between the micro-organic flora and the sourness of the soil. Christensen (67a) found that azotobacter was especially sensitive, its occurrence depending sharply on a sufficiency of base: so much so, indeed, that he uses the presence or absence of azotobacter as a test of the need of adding lime to soil. The test is generally adopted in Denmark. Some of his results are as follows:—

| Percentage of CaO soluble in NH_4Cl | Below 0.05 | 0.06-0.10 | 0.11-0.15 | 0.16-0.20 | 0.20-0.25 | 0.26-0.30 | 0.31-0.35 | 0.36-0.40 | Above 0.4 |
|--|------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| Percentage of cases in which azotobacter develop ¹ | 0 | 0 | 5 | 11 | 44 | 56 | 70 | 91 | 84 |

Nitrifying organisms are also sensitive: they still occur even in acid soils, but their activity becomes much more marked after adding lime. Hall, Miller, and Gimingham² found nitrification going on slowly in the Rothamsted grass plots receiving 600 lb. of ammonium salts annually, and now become so acid that only a few species of plants survive.

¹ The culture solution contains no CaCO_3 but is inoculated with the soil only. Hence the experiment demonstrates the sufficiency or otherwise of the CaCO_3 in the soil for the needs of the organism. A parallel test is made using the full culture solution so as to show whether the organism is present in cases where negative results are obtained.

² *Proc. Roy. Soc.*, 1908, 80 B, 196-212.

The general mixed flora developing on nutrient gelatine plates is also much less numerous on sour than on a neutral soil: Fischer (98) and Bear (11) have both shown marked increases in bacterial numbers after applying lime to soils.¹ The rate of ammonia production does not appear to be so much affected as the numbers of bacteria, but this is explained by assuming that fungi play an increasingly important part in ammonia production as the acidity of the soil increases.² Nevertheless there is on the whole a marked increase in the rates of decomposition of organic matter and of production of nitrate³ when lime is added to soil.

Organisms causing plant diseases also vary in their degrees of tolerance of acidity: in some cases the true acidity was determined. *Pythium*, which produces damping off in seedlings, is somewhat intolerant; consequently no good, and sometimes harm, is done by adding lime to affected soils. Also the organism producing potato scab (*Spongospora subterranea*) is somewhat intolerant, a fact which permits the control of the disease since the potato itself tolerates a higher degree of acidity. Actual measurements by Gillespie and Hurst (105*b*) show that scab is common on the Washburn loams of North Maine where the P_H value is 5.9, but rare on the Caribou loam where the P_H value is 5.2, indicating a higher acidity.

On the other hand, some organisms are more tolerant of acid conditions or even grow better in them. *Plasmodiophora brassica*, producing finger and toe, does so; it is common on acid soils, but is usually kept in check by addition of lime. Further, it is commonly stated that fungi predominate in acid soils, and this may be the case,⁴ but the evidence is rather *a priori* in character, since no satisfactory method of enumeration is known (p. 257).

¹ See also data in Christensen's and Hutchinson's papers.

² Lyon and Bizzell, *Cornell Memoir*, 1, 1913; N. Kopeloff, *Soil Sci.*, 1916, 5: 571.

³ For quantitative measurements see Blair and McLean, *Soil Sci.*, 1916, 1, 489-504.

⁴ It has been noticed at sewage works, *e.g.* at Huddersfield, that fungi develop when the sewage becomes acid through trade effluents

There is the possibility of much useful work in analysing the phenomena of "sourness," and if acidity be the effective agent, in determining the limits of tolerance of acidity by the common crops and disease organisms. The old recommendation to add sufficient lime to ensure neutrality breaks down in the case of potatoes and of certain market garden crops, rhubarb, and in America blueberry,¹ while in other cases it involves an unnecessarily large addition of lime. The object to be aimed at is to keep within certain limits.

Potato growers, whose scheme of cropping includes clover and potatoes, are frequently in an awkward dilemma: if they withhold lime from the soil the clover fails, if they add lime the potatoes become affected with "scab". The ideal arrangement would be to alter the reaction of the soil with each course in the rotation, making it just neutral in the clover year, and in the potato year just sufficiently acid to suppress the "scab" organism. Unfortunately, while it is easy to move in the direction of less acidity, it is difficult to effect the converse change and increase the acidity.²

Are Toxins Present in the Soil?

A persistent idea that one crop may poison another is current among practical men. Early in the last century De Candolle formulated the hypothesis that plants excrete from their roots toxins that remain in the soil for some time and injure other plants of the same species, but not necessarily plants of different species. He thus explained the well-known fact that a rotation of crops is more effective than a system of continuous cropping; in a rotation the toxin excreted by a particular crop is innocuous to the succeeding crop and disappears from the soil before the same plant is sown again.

The hypothesis was tested in a classical research by Daubeny at Oxford (78), but could not be justified. Eighteen

¹ F. V. Colville, *U.S. Dept. Agric. Bull.*, 334, 1915.

² J. C. Lipman has made the interesting suggestion that sulphur could be added to the soil to increase the acidity (*Soil Sci.*, 1919, 7, 181).

different crops were grown continuously on the same plots, and the yields compared with those obtained when the same crops were shifted from one plot to another, so that no crop ever followed another of the same kind. No manure was supplied. The results showed a gradual decrease in the yield in almost every instance, and the decrease was generally greater when the crop was repeated year after year on the same plot than where it was shifted from one to another. Nevertheless the difference between the yields in the two cases was not sufficient to justify any assumption of the existence of a toxin, except perhaps in the case of *Euphorbia lathyris*; in the other seventeen cases it was attributed to the more rapid removal from the continuous plots of the mineral nutrients required by the plant. This explanation was supported by analyses of the plant ash and of the soil—analyses which led to the important distinction between “available” and “unavailable” plant food.

Pot experiments made by the writer at Rothamsted have led to the same conclusions. Six crops of rye were grown in succession in sand to which only nutrient salts were added so as to maintain the food material at a constant amount. A seventh crop was then taken and at the same time a crop was grown on perfectly fresh sand, on which no crop had ever grown before, but which was supplied with an equal amount of the same nutrient salts. There was no significant difference in the two crop yields. A similar experiment was made with buckwheat, another with spinach, and a parallel series was made in soil cultures. In all cases but one the result was the same; the 1910 weights were as follows:—

| | Sand Cultures. | | | Soil Cultures. | | |
|--------------------------------------|--|------------|----------|--|------------|----------|
| | Weight of dry matter found, grams (mean of 4 pots). | | | Weight of dry matter found, grams (mean of 4 pots). | | |
| | Rye. | Buckwheat. | Spinach. | Rye. | Buckwheat. | Spinach. |
| Cropped six times previously | 30·4 | 5·4 | 33·3 | 26·4 | 23·9 | 20·0 |
| Fresh sand or soil . . | 31·3 | 13·5 | 29·5 | 27·1 | 25·2 | 20·8 |

Both sand and soil contained 2 per cent. of calcium carbonate.

If either the rye, buckwheat, or spinach excreted any toxin the amount accumulating during the growth of six successive crops was insufficient to cause any appreciable depression in yield in the next crop ; the exceptional result given by buckwheat in sand could not be confirmed.

These and similar experiments show that no lasting toxic effect is produced by any of the crops studied, and they rule out any toxin hypothesis as an explanation of the advantages of rotations¹ where there is always a lengthy interval between the crops. They do not, however, show that there is no transient effect, and they are thus quite consistent with some remarkable observations by Pickering on the effect of grass on apple-trees (225*a*). It was found at Woburn—and the observation has since been confirmed elsewhere—that the effect of growing grass round apple-trees is to arrest all healthy growth and absolutely stunt the tree. The leaves become unhealthy and light coloured, the bark also becomes light coloured, while the fruit loses its green matter and becomes waxy yellow, or brilliant red. Where the grassing was done gradually the trees accommodated themselves somewhat to the altering conditions, but never grew so well as when grass was absent.

This effect might have been due to various causes : changes in aeration, temperature, water supply, food supply, or physical condition of the soil, but careful experiments failed to show that any of these factors came into play. Covering the soil with cement excluded air at least as thoroughly as grass, and yet did not produce the grass effect, nor was it suppressed by wet seasons, liberal watering, or a supply (in pot experiments) of sufficient water or nutrient solution to keep the soils of grassed and ungrassed trees equally moist, or equally well supplied with food. On the other hand, the grass effect was produced when perforated trays of sand containing growing grass were placed on the surface of the soil in which trees were growing, so that the washings from the grass went straight down to the tree roots. There seemed no possibility

¹ Some curious problems are thus left unsolved, some of which are discussed more fully by the author in *Science Progress*, July, 1911, p. 135.

of the grass roots in the trays abstracting anything from the soil, and the only explanation appears to be that a toxin is excreted by the grass. Such a toxin, however, must be very readily decomposed, because no toxic properties could be discovered by laboratory tests either in soil that had been removed from the grass roots or in the washings from the above-mentioned trays. Pickering has since shown that the phenomena are general and hold whatever crops are grown in the pots and trays. In consequence we must be prepared to consider possible toxic effects of one plant on another *growing alongside of it*, and the part such effects may play in determining natural plant associations and in explaining some of the bad effects of weeds.

Pickering's results agree with the hypothesis already put forward by Whitney, and developed by him and Cameron, Schreiner (306, 65c, 249, etc.) and their colleagues at the Bureau of Soils, Washington. Certain soils are supposed to contain toxins, which are not necessarily plant excretions, but may arise by decomposition of organic matter in the soil. The genesis of this hypothesis is interesting. Reference has already been made to Whitney's view that the soil solution furnishes the food of plants and is of the same composition and concentration in all soils, from which it follows that infertility of any soil cannot be due to lack of food. But in certain cases this infertility is transmitted to the aqueous extract of the soil, and must, therefore, arise from some soluble toxin. As an example Whitney and Cameron (305) selected two Cecil clays of very different productiveness but of identical chemical and physical constitution, prepared aqueous extracts and used them as culture solutions for wheat seedlings. The extracts contained in parts per million:—

| | NO ₃ . | PO ₄ . | K. | Ca. |
|---------------|-------------------|-------------------|-----|-----|
| Good soil . . | 3.2 | 1.6 | 3.6 | 3.2 |
| Poor soil . . | 3.5 | 1.6 | 2.0 | 2.8 |

and were thus identical in their content of plant nutrients ;

they were also both neutral. Yet they produced very different effects on the wheat seedlings: the "good soil" extract caused a larger and healthier development of root and a somewhat better development of leaves. In other cases it has been found that growth in extracts of poor soils is even worse than in distilled water. The productiveness of the extract could be raised, according to Livingstone (179), by dilution, shaking with calcium carbonate, precipitated ferric or aluminium oxide, animal charcoal, or soil; results which are explained by supposing that these agents precipitate a toxin. Addition of fertilisers, and especially of an aqueous extract of farmyard manure, improved the solution; these substances also were supposed to precipitate the toxin.

A double set of experiments was therefore begun by Schreiner and his colleagues; a careful search was made in the soil for such organic compounds as could be identified (see p. 141); and the effect of these and similar compounds on plant growth was studied by elaborate water cultures. Considerable attention has been devoted to dihydroxy-stearic acid. This substance is toxic to plants in water culture, and is almost invariably present in infertile soils, especially such as are badly drained, badly aerated, too compact, and deficient in lime (251); soils, in short, that in England are called "sour".

On the other hand, Russell and Petherbridge could obtain no aqueous extract toxic to plants from greenhouse "sick" soils. These soils, however, are rich in organic matter, in plant food, and in calcium carbonate.

The present position may briefly be summed up as follows: There is no evidence of the presence of soluble toxins in normally aerated soils sufficiently supplied with plant food and with calcium carbonate, but toxins may occur on "sour" soils badly aerated and lacking in calcium carbonate, or on other exhausted soils. There is no evidence of any plant excretions conferring toxic properties on the soil, but the Woburn fruit-tree results show that a growing plant may poison its neighbour. The effect does not appear to be speci-

fic; any plant will be injured by any other within its range, and it may suffer less from one of another kind than from one of its own kind.¹

Bacterio-toxins.—Several observers, including Greig-Smith (114), Bottomley (42), and others, have claimed to find soluble bacterio-toxins in soils. Hutchinson and Thaysen (1408), on the other hand, obtained wholly negative results, and concluded that soluble bacterio-toxins are not normal constituents of soils, but must represent unusual conditions wherever they occur. But the possibility of the existence of toxins insoluble in water still remains.

Normal Conditions on a Heavy Soil.

Table LXVI. summarises many of the Rothamsted results and shows the conditions normally obtaining on a heavy soil in Hertfordshire under a rainfall of 28.30 inches.

TABLE LXVI.—CONDITIONS NORMALLY OBTAINING IN THE SOIL AT ROTHAMSTED.

| Manurial Treatment of Soil. | | Soil Moisture.* | | Total Nitrogen. | | Nitrogen as Nitrate. | | Numbers of Bacteria, Millions per grm. | CO ₂ in Soil Air. |
|------------------------------------|---------|--------------------|---------|-----------------------|-----------------|-------------------------|------------------|--|------------------------------|
| | | Per Cent by | | Parts p r Million. | Lb per Acre. | Parts per Million. | Lb. per Acre. | | |
| | | Volume. | Weight. | | | | | | |
| No manure | Cropped | 23.12 | 15.8 | 990 | 2500 | (top 9") | | 7.12 | 0.2.0.6 ² |
| Condition poor | Fallow | 23 | 15 | | | 5.12 | 12.30 | | |
| | | | | | | 8.15 | 20.36 | 7.12 | 0.2.0.4 |
| Farmyard manure | Cropped | 30.15 | 17.8 | 2200 | 5000 | 10.20 | 25.50 | 15.25 | 0.5.1.0 ³ |
| Condition good | Fallow | 30 | 17 | | | | | | |
| Ordinary arable field | Cropped | 25.12 | 15.8 | 1500 | 3700 | 10.15 | 25.36 | 15.25 | 0.5.1.0 ⁴ |

¹ Thus Burmeister (*Fühl. Landw. Zeit.*, 1914, 63, 547-556; see *Rome Bull.*, 1914, 1691) found that couch (*Triticum* or *Agropyron repens*) increased the yield of oats, and Dr. Brenchley found that certain weeds had the same effect on the yield of wheat *per plant* (*New Phytologist*, 1917).

² Running on occasions up to 1.8.

³ Occasionally up to 2.3.

⁴ Occasionally up to 2.5.

* The concentration of the dissolved matter is of the order of 0.2 per cent. and the osmotic pressure about 1 atmosphere.

CHAPTER VII.

THE MICRO-ORGANIC POPULATION OF THE SOIL AND ITS RELATION TO THE GROWTH OF PLANTS.

THE soil is inhabited by a great variety of micro-organisms, but their precise relationship to the growing plant is difficult to determine because we know so little about them. The micro-organic population is certainly highly complex: it is known to contain many kinds of bacteria, moulds, protozoa and other organisms, and new members are discovered almost every month.

Usually they are picked out by some culture method, and their physiological effect is studied in an arbitrary culture solution: sometimes the results are applied straightway to the soil without further ado. The method is defective for two reasons. Firstly, micro-organisms are considerably influenced by the medium in which they happen to find themselves, and may effect one change under one set of circumstances but quite another change under other circumstances. Secondly, most micro-organisms exist in two states: an active or trophic state, and a resting state, and it is reasonable to suppose that the resting forms are comparatively unimportant. Probably in many cases no sharp line exists between the two, the active forms changing to the resting stage or back again as the soil conditions alter; but it is never safe to assume without proof that any organism discovered by culture methods is active in the soil. The main difficulty in applying the results is that soil cannot be sterilised¹ because of its chemical instability, nor can it be made up artificially; in consequence one cannot begin with a sterile soil and inoculate into it a particular set

¹ Intermittent sterilisation at 80° causes less decomposition, but it does produce change (D. A. Coleman, H. C. Lint, and N. Kopeloff, *Soil Sci.*, 1916, 1, 259).

of organisms so as to observe their behaviour under natural conditions. These difficulties have not proved insuperable, and a number of organisms have been discovered which normally lead a trophic life in the soil. These organisms may be regarded as the micro-organic population of soil.

The essential conditions for the life of a micro-organic population are adequate supplies of food and energy materials, sufficient air and water, a proper range of temperature, and absence of harmful factors. With the exception of the energy supply these requirements are the same as for higher plants; and as many of the nutrients are common to the plant and to micro-organisms it is not surprising that soils well suited to the growth of plants often carry a large population of micro-organisms also.

Investigators have long realised that soils contain numbers of bacteria, and in Chap. V. some of the changes they bring about are described. Evidence has been accumulated that other groups of micro-organisms are normally present also—fungi, algæ, protozoa, nematodes, etc.

In previous editions of this book the organisms were classified according as they were or were not useful to plants. This scheme is useful as a first approximation, but it does not admit of fuller development: it is therefore discarded in the present edition. The members of the soil population must be regarded as leading their own lives and, with few exceptions, possessing powers of adaptation which enable them to draw sometimes on one compound and sometimes on another for food and for energy, and therefore not necessarily always producing the same substances. The mycoides, for example, where they are active, can produce ammonia from protein and would then be helpful to plant growth; under other circumstances, however, they assimilate ammonia and therefore compete with growing plants.

Certain broad relationships have been established between the various members of the soil population, and between the population as a whole and the growing plant: there is evidence for the following propositions:—

1. The population at any given moment is as large as the conditions allow, and is limited by presence of a harmful factor or by lack of some essential factor such as energy supply, food supply, air, water, or temperature. Improvement in the supply of the limiting factor, or removal of the harmful factor, allows an increase in numbers of the population.

2. Competition therefore is an important factor in determining the relative numbers of the various groups: any increase in the numbers of one group may lead to a decrease in the numbers of others having similar requirements. Changes in numbers of any one group, therefore, are not necessarily sharply related to changes in external conditions, and when the external conditions are brought back to their original level the numbers of any one group may not return to what they were before.

3. Owing to the great differences in size the numbers of the various groups do not allow a ready basis of comparison. The most suitable basis for quantitative comparisons between one group and another is their respective energy requirements: these are comparable. Bacteria, fungi, protozoa, and nematodes are all consumers: algæ only are producers of energy materials.

The relationships of the soil population to the growing plant are as follows:—

1. The energy supplies in the soil come from the residues of green plants. Since energy supply is probably the most important factor limiting the numbers of the soil population it follows that the soil population is to this extent dependent on the plant.

2. But the plant is also dependent on the soil population since the soil population in its search for energy supplies decomposes so much protein substance with formation of ammonia and of nitrate as to leave over a surplus for the plant. Further, certain members of the population also decompose materials such as straw, etc., which possess definite structure and have undesirable physical effects on the soil, while other members decompose toxins such as phenol, which they accumulated would be harmful to the plant.

3. During the growth of the plant some at any rate of the soil organisms appear to be adversely affected : some of the activities of the growing plant seem to be detrimental to the micro-organic population.

4. While sharp distinctions cannot be drawn some groupings of the micro-organic population are more conducive to the production of plant nutrients than others, and some organisms are definitely harmful to the plant.

Organisms Acting Directly on the Plant.

(1) *Parasitic and Disease Organisms.*

The study of these organisms has developed into a special branch of Economic Biology, and we need therefore only briefly refer to them here. The commonest are the eel-worms, the myxomycete *Plasmodiophora*, some of the " wilts," and certain organisms that attack potatoes.

Of the numerous kinds of eel-worms occurring in the soil, about six are known to attack and enter the plant, and do considerable direct injury, besides opening the way for the entrance of fungi, bacteria, etc. The commonest are *Heterodera radiculicola*, which causes swellings or " knots " on the roots of tomatoes, cucumbers and other plants, and *Tylenchus dipsaci* (*syn. devastatrix*) which attacks oats, causing tulip root, and clover, bringing on one form of clover sickness. In some soils, especially those short of lime, another pest is common : the myxomycete *Plasmodiophora*, which enters the roots of swedes, turnips and other plants of the *Brassica* tribe, causing the disease known as finger-and-toe.

(2) *Symbiotic Organisms.*—In normal conditions leguminous plants possess nodules on their roots which contain numbers of bacteroids living in association with the plant. This organism, *Bacillus radiculicola*, enters the plant roots at an early stage and, having brought about the formation of the nodule, proceeds to manufacture nitrogen compounds for the plant from the gaseous nitrogen of the air (see p. 204.)

Certain trees and shrubs (notably beech, heather, etc.) become associated with mycorrhiza, fungi which grow on their

roots and aid in the nutrition of the plant. These were first investigated by Frank and have received considerable attention from mycologists.¹

Organisms Capable of Bringing About Changes of Importance to the Plant.

1. *Algæ.*

All soils hitherto examined contain algæ including diatoms, green and blue-green algæ, and the flora seems to be particularly well-developed in cultivated soils. F. Esmarch² studied the soil flora of the German African colonies and of Schleswig-Holstein, W. W. Robbins³ that of the Colorado, and J. B. Petersen⁴ the diatoms of the Danish soils; Dr. B. Muriel Bristol of Rothamsted⁵ the flora of certain English soils. The algæ occur to a depth of 12 inches and in some cases even 2 feet; the species in the lower layers are almost identical with those at the surface.

It is now known that certain algæ can develop in darkness provided suitable nutrients are present, and assuming these conditions there is nothing against the possibility of a trophic alga-flora in the soil. Esmarch attempted to obtain positive evidence by burying algæ in the soil and making microscopic examinations after given intervals of time; in these circumstances the blue-green algæ retained their colour for some weeks, but ultimately became yellowish, and the filaments disintegrated.

¹ B. Frank's paper is in *Botan. Ztg.*, 1891, 9, 244-253, where references to his earlier papers are given. Recent investigations have been made by M. C. Rayner, *Annals of Botany*, 1915, 29, 97-133.

² F. Esmarch, *Beitrag zur Cyanophyceen-Flora unserer Kolonien* (*Fahrbuch der Hamburgischen wissenschaft. Anstalten*, xxviii., 3 Beiheft, 62-82, 1910). *Untersuchungen über die Verbreitung der Cyanophyceen auf und in verschiedenen Boden* (*Hedwigia*, Band lv., Heft 4-5, September, 1914).

³ W. W. Robbins, *Algæ in some Colorado Soils* (*Bulletin* 184, *Agri. Exp. Sta.*, Colorado, June, 1912).

⁴ J. B. Petersen, *Danske aerofile alger* (*D. Kgl. Danske Vidensk. Selsk. Skrifter*, 7, Raekke, *Naturv. og Mathem.*, Afd. xii, 7, 1915).

⁵ B. M. Bristol, *On the Alga-Flora of some Desiccated English Soils* (*Annals of Botany*, 1920, 34, 35-80).

Considerable numbers of species have been found, but estimates of total numbers are rendered uncertain by the breaking up of the filaments during the laboratory operations.

There has been some speculation as to the possible function of algæ in the soil. Assuming that they continue to assimilate CO_2 they are, of course, accumulators of energy and of carbohydrate material, and while they may thus function at the surface in the light it is difficult to see how they can be other than consumers in the dark recesses of the soil. The possible effects of this accumulation of organic matter in newly formed soils is discussed by Treub¹ in his account of the recolonisation of Krakatoa after the eruption of 1886, and by Fritsch.²

There is also the possibility that algæ may take part in nitrogen fixation in the soil. It was at first thought by Frank³ and by Schloesing and Laurent⁴ that algæ could themselves fix nitrogen, and this view has recently been revived by Moore and Webster.⁵ Kossowitsch,⁶ however, maintained that they cannot, bacteria alone having this power. He observed, however, that the presence of algæ facilitated the process, and concluded that symbiosis occurs between algæ and nitrogen-fixing bacteria, the algæ supplying the necessary carbohydrate energy material and the bacteria furnishing the nitrogen required for growth. Nakano⁷ shows that the relationship with *azotobacter* holds not only for blue-green but also for certain green algæ.

¹ Treub, *Notice sur la Nouvelle Flore de Krakatau* (Ann. Jard. bot. Buitenzorg, Vol. 7, 1888, p. 213).

² F. E. Fritsch, *The Role of Algal Growth in the Colonisation of New Ground and in the Determination of Scenery* (Georg. Journ., November, 1907).

³ B. Frank, *Ueber den experimentellen Nachweis der Assimilation freien Stickstoffs durch erdbodenbewohnende Algen* (Ber. der D. Bot. Ges., vii., 1889, pp. 34-42).

⁴ Schloesing, fils, and E. Laurent, *Recherches sur la fixation de l'azote libre par les plantes* (Ann. de l'Institut Pasteur, vi., 1892, p. 65-115).

⁵ Proc. Roy. Soc., 1920, B. 91, 201.

⁶ P. Kossowitsch, *Untersuchungen über die Frage, ob die Algen freien Stickstoff fixiren* (Bot. Zeit., 1894, Heft 5, pp. 98-116).

⁷ H. Nakano, *Untersuchungen über die Entwicklungs- und Ernährungsphysiologie einiger Chlorophyceen* (Jour. of Coll. of Science, Imperial Univ., Tokyo, vol. xl., 1917, Art. 2, p. 66, etc.).

Bouilhac¹ and Giustiniani² showed that in sand free from organic matter and nitrogen compounds, soil bacteria and algæ not only develop normally, but also enrich the soil with nitrogen sufficiently to support the growth of higher plants; while still more recently Pringsheim³ has shown that the ability of bacteria to fix nitrogen is closely dependent upon the presence of blue-green algæ (see p. 200).

A third possibility discussed by Gautier and Drouin⁴ is that algæ may assimilate ammonia or nitrate in the soil and convert it into complex organic substances. The existence of an action of this kind in normal soils has been indicated by Russell and Richards (241*k*).

Harrison and Aiyer (126) maintain that algæ serve a special purpose in swamp soils, taking in CO₂ and giving out oxygen, which is then available for the plant roots.

2. Fungi.

It has long been known that fungi occur in the soil, and as long ago as 1886 no less than eleven different species were isolated by Adametz.⁵ Subsequent workers have greatly enlarged the list and more than 200 species have now been described as soil fungi.

The investigations have fallen into several groups. Some workers, as Butler⁶ in India, Hagem⁷ in Norway, and Lendner⁸

¹ R. Bouilhac, *Sur la fixation de l'azote atmosphérique par l'association des algues et des bactéries* (Compt. Rend., cxxiii., 1896, pp. 828-830).

² R. Bouilhac and Giustiniani, *Sur une culture de sarrasin en présence d'un mélange d'algues et de bactéries* (Compt. Rend., cxxxvii., 1903, pp. 1274-6).

³ E. Pringsheim, *Kulturversuche mit chlorophyllführenden Mikro-organismen.*, III. *Zur Physiologie der Schizophyceen* (Cohns, Beiträge z. Biol. d. Pflanzen, Bd. xii., pp. 99-107).

⁴ Gautier and Drouin, *Recherches sur la fixation de l'azote par le sol et les végétaux* (Compt. Rend., cvi., 1888, pp. 754, 863, 944, 1098, 1174, 1232, 1605).

⁵ L. Adametz, *Untersuchungen über die niederen Pilze der Ackerkrume* (Inaug. Diss., Leipzig, 1886).

⁶ E. J. Butler, *An Account of the Genus Pythium and some Chytridiaceæ* (Mem. Dept. Agric., India, Bot. Ser., 5, 1, 1-160, 1907).

⁷ O. Hagem, *Untersuchungen über norwegische Mucorineen* (Videns. Skrift. I., Math. Nat. Kl., 1907, No. 7; Part II., 1910, No. 4).

⁸ A. Lendner, *Les Mucorinées de la Suisse*, Berne, 1908.

in Switzerland, have confined themselves mainly to particular types, and have not attempted a comprehensive survey of the whole field. Others have tried to ascertain how far facultative parasitic fungi could live saprophytically in the soil: apparently certain disease-producing *Fusaria* and *Pythium* can do this. Pratt¹ has isolated fungi which cause disease in potatoes from virgin desert lands and also from Idaho soils that have never been cropped with potatoes.

The more serious problem of studying the fungus flora of the soil as a whole has been attempted in Holland by Oudemans and Koning (221), in the United States by Waksman (292c), and in England by Miss E. Dale (75). It is now under investigation at Rothamsted by W. B. Brierley and Miss S. T. Jewson.

The great difficulty is the lack of suitable methods of investigation: neither the morphologists nor the physiologists have yet developed precise, simple methods. The fungi are invariably isolated from the soil by means of cultural media, but there is no means of ensuring that the medium used is suitable for the development of all forms that may be present: many of the parasitic forms and others in addition are doubtless missed. Further, the morphological characters vary with different media:² hence it is impossible to describe the organisms as they exist in the soil. Nor are the physiological properties any more definite: they depend on the condition of the organism—the newly germinated fungi behaving differently from the older mycelium.

In these circumstances rigid identification is a matter of great difficulty and it is impossible to reprehend too strongly the practice, so tempting to pioneers, to describe forms as new species, unless careful examination of their behaviour on different media has shown that they really are new.

Again, there is no method of estimating even approxi-

¹ O. A. Pratt, *Journ. Ag. Res.*, 1918, 13, 73-100.

² For a discussion of the phenomena see W. B. Brierley, *Some Concepts in Mycology—An Attempt at Synthesis* (*Trans. Brit. Mycol. Soc.*, VI., part 2, 1919).

mately the numbers of various fungi in the soil. When used for fungi, the plating methods devised for bacteria and for protozoa suffer from the drawback that they involve the breaking up of pieces of mycelium and the scattering of clusters of spores, with the result that a single fragment of fungus in the soil might appear as hundreds or even thousands of individuals on the plates.

Finally, there is great difficulty in ascertaining the physiological effects of the soil fungi. Because a fungus brings about a particular reaction in a culture medium it by no means follows that the same reaction will occur in the soil where the conditions and the compounds are wholly different.

In these circumstances the only safe method is to accumulate observations and interpret them cautiously. The existence of a fungus flora is undoubted, and it is largely confined to the top 6 inches of soil. Formerly it was supposed (and the view was emphasised by Ramann, 233*a*) that fungi predominated in acid soils, and bacteria in neutral soils, but the evidence is not beyond criticism: fungi can, however, certainly produce and tolerate acidity. Little can be stated as to relative numbers in grass and arable land, or in poor and rich soils. The species most frequently found in temperate regions, and therefore presumed to be commonest, are the *Penicillia* and *Mucors*: in addition *Fusarium*, *Aspergillus*, *Trichoderma* and *Cladosporium* are common. In the warmer Southern States, however (*e.g.* Texas), Waksman (292*d*) found *Aspergillus* more frequently than *Penicillium*. In the absence of quantitative methods of estimating numbers or of physiological methods of estimating activity it is impossible to say how fungal activity varies with soil conditions.

Like all other living organisms fungi require sources of energy and of nitrogen. All species can obtain their energy supply from various carbohydrates, and most species can obtain it from cellulose, in which respect fungi differ from many bacteria. McBeth and Scales (185*c*) found the most active cellulose decomposers to be the *Penicillia*, *Aspergilli*, *Trichodermæ* and *Verticillia*: on the other hand, the *Mucorales*

apparently effect little or no decomposition of cellulose (292*d*). The chemical changes involved are unknown, but it is unlikely that the reaction would proceed by itself in the soil; in all probability the soil bacteria would participate.

When ample supplies of carbohydrate (including cellulose) are present, the most economical nitrogen nutrients are the amino-acids (Czapek).¹ In absence of sufficient supplies of carbohydrate, Waksman shows that the fungi can obtain both energy and nitrogen from soil protein compounds, but in this case more degradation occurs than is necessary to supply the nitrogen required, and consequently ammonia remains over (292*d*). Under suitable conditions certain fungi (e.g. *Trichoderma Koningi*) can produce ammonia more rapidly than bacteria (McLean and Wilson, 188). Fungi have no power of oxidising ammonia to nitrates. They can, however, readily assimilate both ammonia and nitrates, and they have been supposed by Ehrenberg (93*c*) to cause considerable locking up of these compounds in the soil (see p. 210).

It was at one time thought that fungi could fix gaseous nitrogen, but Duggar and Davis,² in a careful series of experiments, were unable to obtain evidence that any fungus excepting *Phoma Betae* possessed this property.³

It is impossible on present knowledge to assess the importance of fungi in soil fertility. The decomposition of cellulose is undoubtedly beneficial and probably justifies the old view that fungi are the humus formers of the soil (Ramann, 233): on the other hand, the locking up of nitrogen compounds is a disadvantage which, however, would be considerably counterbalanced if the substance of the mycelium were readily decomposable by bacteria on the death of the organism.

3. *Actinomyces*.

This group of organisms, sometimes included in the fungi and sometimes in the bacteria, is of frequent occurrence in the

¹ *Beit. Chem. Physiol. u. Path.*, 1901-2, **1**, 538; **2**, 557; **3**, 47.

² *Ann. Mo. Bot. Gard.*, 1916, **3**, 413-437.

³ According to Ternetz (*Jahrb. f. wiss. Bot.*, 1907, **44**, 353-408) *Phoma radici* can also assimilate gaseous nitrogen.

soil. Conn (70*b*) estimated that they were one-quarter as numerous as the bacteria in arable soil and one-half as numerous in grassland. It is very doubtful, however, whether any counting method is reliable. Waksman and Curtis (292*e*) have made an extensive study of this group¹ and have described thirty or forty soil species. Apparently the actinomycetes decompose cellulose though they do not readily produce ammonia from protein. It is said also that they can reduce nitrates to nitrites.

4. *Bacteria.*

From time to time indications have been obtained that some of the soil bacteria bring about changes harmful to the plant, but the evidence is insufficient to justify any detailed discussion. It has been supposed that plant toxins are produced (p. 247), that soil nitrates are assimilated (p. 210), and that the food, air, and water which should otherwise be available to the plant are taken up by the micro-organisms.²

The subject that has been most frequently investigated is the part played by soil bacteria in the decomposition of the organic matter of the soil and the production of nitrates. Both changes are brought about by bacteria and they are of such obvious advantage to the plant as to suggest that relationships ought to exist between bacterial activity and the growth of plants. Several methods have been adopted to trace such relationships.

The direct method consists in picking out definite organisms and studying them in conditions calculated to throw light on their action in the soil. This has proved very difficult, and has been successfully achieved only by a few of the best bacteriologists; instances are afforded by the work of Winogradsky (pp. 187, 196), Beijerinck (p. 197) and others.

Three indirect methods have therefore been used:—

¹ For a morphological study see Charles Drechsler (*Bot. Gaz.*, 1919, 67 65-83, 147-168).

² See, e.g., Dačnowski (Ohio), *Expt. Sta. Record*, 1910, 23, 122.

(1) Soil is inoculated into various media each arranged to bring out one group of organisms, and the amount of decomposition is taken as a measure of the number and vigour of the members of the group. This is often called the method of physiological grouping.

(2) Platings on gelatin or agar media are made of soil suspensions suitably diluted, and the colonies which develop are counted. The results are expressed as millions of bacteria per grm. of soil.

(3) Chemical analyses are made at stated intervals to determine the rate of progress of the various changes going on—the absorption of oxygen, the evolution of carbon dioxide, the production of nitrates, etc.

The difficulty with the first or direct method is to imitate the soil conditions, and the history of the subject affords many instances of the danger of getting away from them: for example, Krzemieniewski's work on the nitrogen-fixing organisms may be quoted (p. 199). It is impracticable, for reasons already given, to keep to the soil as the medium for work, and most investigators have therefore used the indirect methods.

Physiological Grouping.—This method was introduced by Remy (237*a*) and developed by Löhnis (182); it has become very popular. Four distinct media are in use, arranged respectively to favour nitrification, ammonia production, nitrogen fixation, and denitrification. The experiments are easy to carry out, but they require skilful interpretation, and the results may prove treacherous unless carefully handled. The fundamental objection to the method is that the reaction goes on in a medium very different from ordinary soil, so that it throws no light on the relationships obtaining in the soil itself. The results really only prove that the bacteria from one soil will flourish better in a certain artificial medium than those from another.

The medium for studying nitrification is usually that suggested by Omelianski or Ashby's modification (p. 188); it is inoculated with a definite weight of soil and incubated: the

nitrates produced after a certain time are determined. By working under uniform conditions (which each investigator fixes for himself) the results obtained are comparable for the series of soils under investigation.¹ The amount of nitrate produced by unit weight of soil is called the "nitrifying power". The actual figure is obviously arbitrary, depending on the conditions selected, and it has meaning only in relation to the other soils in the same set of experiments. Several investigators, however, have found that nitrifying power shows some relation to plant growth, the soils most favourable to plants having, on the whole, the highest nitrifying power. This result has been obtained by Gainey in Kansas²; C. B. Lipman in California³; G. P. Given in Pennsylvania⁴; Percy Brown in Iowa (60*a*); P. S. Burgess in Hawaii (63); at Rothamsted by Ashby (7*a*); and at Fallon, Nevada, by Kellerman and Allen⁵; some of the data are given in Table LXVII.

TABLE LXVII.—NITRIFYING POWERS OF VARIOUS SOILS OF KNOWN PRODUCTIVENESS.

| Ashby, Rothamsted (7 <i>a</i>). | Nitrifying Power. | Kellerman and Allen (Fallon, Nevada) (Order of Productiveness). | Nitrifying Power. | Bacterial Numbers. Millions per gram. |
|--|----------------------|---|----------------------|--|
| Agdell Field, A. 3, } most productive } | 93 | Very productive | 54 | 0'02 |
| Agdell Field, A. 2, } intermediate } | 38 | Pro- { Plot 40 ductive { Plot 190 plots { Plot 290 | 20 36 30 | 0'21 0'003 0'27 |
| Agdell Field, A. 1, } poorest } | 26 | Poor { Plot 10 Plot 30 Plot 180 | 4 3 5 | 0'44 0'16 0'06 |

Withers and Fraps (313) have modified the method, and use sterilised soil as the medium for the growth of the

¹ For a statistical study of the magnitude of the error see D. D. Waynick. *Univ. Calif. Pub. Ag. Sci.*, 1918, 3, 243.

² *Soil Sci.*, 1917, 3, 339-416.

³ *Proc. Soc. Prom. Agr. Sci.*, 1914, 33-39, and *Cal. Bull.*, 260, 107-127.

⁴ *Penn. Rept.*, 1912-13, 204-206.

⁵ *Bacteriological Studies of the Soil of the Truckee-Carson Irrigation Project*. Karl F. Kellerman and E. R. Allen (U.S. Dept. of Agric. Bureau of Plant Industry, *Bull.* No. 211, 1911). See also Ehrenberg (93*b*).

organisms. A careful distinction must be made between the nitrifying power ascertained from culture media and the rate at which nitrates accumulate in the soil. The experiments in culture media measure the rate of nitrification under the circumstances of the experiment: the accumulation of nitrate in the soil, on the other hand, measures the rate of ammonia production (p. 188).

The "ammonifying power" or "putrefactive power" is determined by inoculating soil into a 1 per cent. peptone solution, and determining the ammonia formed after incubation at 20°. Remy found that certain soils known to give good crop returns for organic manures also possessed high putrefactive power. He incubated for four days, but Russell and Hutchinson (241*c*) obtained better results by taking definite intervals and plotting curves showing the respective rates of ammonia production by the different soils. Löhnis has used this method a good deal (181*b*) as also has J. G. Lipman, who, however, modifies it considerably, and among other things uses sterilised soil as the medium and substitutes dried blood or cotton-seed meal¹ for peptone (176). Percy Brown (60) used a similar modification in his studies of Iowa soils, and found that the "ammonifying power" ran along with the "nitrifying power" and, in four out of the six plots, with the crop-producing power also (Table LXVIII.).

Other workers have observed a general similarity between ammonifying power and productiveness which, however, frequently breaks down in individual cases. Further, the differences between good and poor soils are not particularly marked and would often be considered to lie within the error of the experiment. The relationship with productiveness is therefore less definite than in the case of nitrification.²

¹ Sackett (*Colorado Bull.*, 184, 1912) has shown that these cannot be used indiscriminately; in some soils dried blood is ammonified more rapidly than cotton-seed meal while in others the reverse holds.

² For evidence to this effect see P. S. Burgess (63), Gainey, *Soil Sci.*, 1917, 3, 399; Kelley, *Science*, 43, 30-33, and *Hawaii Bull.*, 37, 1915, p. 52; Stevens and Withers (271); J. G. Temple, *Ga. Bull.*, 126, 1919.

TABLE LXVIII.—BACTERIAL ACTIVITY IN SOILS OF KNOWN PRODUCTIVENESS.
P. E. BROWN (1904). IOWA SOILS.

| Plot No. | Yield of Maize, Bushels per Acre. | History. | Ammonifying Power. | Nitrifying Power. | Nitrogen-Fixing Power. | Bacterial Numbers, Millions per gram. |
|----------|-----------------------------------|---|--------------------|-------------------|------------------------|---------------------------------------|
| 607 | 52.7 | 2 year rotation, maize, oats, clover ploughed in | 175 | 7.1 | 14.3 | 2.8 |
| 604 | 50.7 | 3 year rotation, maize, oats, and clover | 189 | 12.6 | 20.6 | 3.3 |
| 602 | 46.0 | 2 year rotation, maize and oats | 178 | 8.1 | 17.5 | 2.6 |
| 901 | 43.2 | 2 year rotation, maize, oats, rye ploughed in | 175 | 6.7 | 14.3 | 2.5 |
| 601 | 35.5 | Continuous maize | 171 | 5.0 | 9.5 | 2.1 |
| 609 | 32.5 | 2 year rotation, maize, oats, cowpeas ploughed in | 180 | 11.9 | 18.2 | 2.7 |

P. S. BURGESS (1933). HAWAII SOILS. (Plots Grouped in Order of Merit.)

| | Best. | Very Good—not Placed in Order. | | | | | Poorer. | | Least |
|---|-------|--------------------------------|------|------|------|------|-----------------------|------|-----------------|
| Yield of sugar: Plot No. | 2 | 1 | 8 | 4 | 6 | 3 | 5 | 7 | 9 |
| Ammonification: dried blood: Plot No. | 2 | 1 | 9 | 4 | 6 | 8 | 3 | 7 | 5 |
| Mgrms. of added nitrogen ammonified after 10 days | 100.2 | 76.4 | 75.9 | 74.5 | 68.6 | 57.7 | 57.1 | 47.6 | 26.6 |
| Alfalfa meal | 2 | 9 | 3 | 6 | 4 | 8 | 1 | — | 5 |
| Mgrms. of added nitrogen ammonified after 10 days | 14.8 | 14.0 | 12.9 | 11.2 | 9.8 | 9.5 | 6.7 | — | 14 |
| Nitrification: dried blood | 2 | 3 | 4 | 6 | 8 | 1 | 7 | 5 | 9 |
| Mgrms. of added nitrogen nitrified after 30 days | 20.8 | 20.0 | 18.0 | 17.2 | 16.8 | 15.2 | 13.6 | 4.0 | 4.0 |
| Alfalfa meal | 2 | 7 | 4 | 3 | 8 | 6 | 1 | 5 | 9 |
| Mgrms. of added nitrogen nitrified after 30 days | 15.2 | — | 12.8 | 12.0 | 10.0 | 9.6 | 9.0 | 7.2 | 4.5 |
| Nitrogen rendered water soluble: dried blood | 9 | 2 | 6 | 3 | 4 | 8 | 7 | 1 | 5 |
| Mgrms. of nitrogen recovered after 20 days | 31.1 | 29.4 | 27.0 | 24.4 | 23.9 | 22.8 | 22.3 | 18.3 | 10.3 |
| Nitrogen fixation (mannite solution) | 2 | 8 | 6 | 4 | 3 | 1 | 7 | 9 | 5 |
| Mgrms. nitrogen fixed per grm. of mannite | 11.20 | 10.64 | 7.28 | 7.00 | 6.44 | 5.60 | 3.92 | 3.60 | 2.20 |
| Good Azotobacter surface membrane. | | | | | | | Doubtful Azotobacter. | | No Azotobacter. |

"Nitrogen-fixing power" is measured by inoculating soil into Beijerinck's or some similar solution (p. 197) and incubating for a definite time. This reaction proceeds only slowly. The results usually show a general resemblance to those given by nitrification experiments.¹

Bacterial Counts.—The method of counting the number of colonies that develop on gelatin or agar plates is admittedly faulty, but it has the advantage of showing whether the numbers are high or low and whether they are increasing or decreasing. It has, unfortunately, three serious defects. No medium is known that brings out all the soil organisms, so that the results are invariably low,² and their quantitative appearance is wholly illusory. No medium even distantly resembles the soil in composition or in structure, so that the flora developing on the plates does not necessarily reflect the flora active in the soil; in particular it is impossible to tell which of the forms developing on the plate are active and which are spores in the soil. Account is seldom taken of the kinds of bacteria on the plates; in practice it proves far too laborious to attempt any but the simplest identifications.

This disregard of the nature of the bacteria constitutes a fundamental distinction from the method dependent on physiological grouping, and the two methods do not always give similar results. The counts show fairly correctly whether any given treatment of the soil has raised or has lowered the number of bacteria, but unless the change has been drastic they do not show whether all varieties have been equally affected. Thus they have always to be combined with determinations of the amounts of ammonia and nitrate in the soil.

Chemical Analysis in Conjunction with Bacterial Counts.—The third method of making bacteriological counts in conjunction with chemical analysis, has been largely used in the Rothamsted laboratories. Increases in bacterial numbers are so often associated with increased production of nitrate as

¹ E.g. see papers by P. E. Brown; also P. S. Burgess.

² Comparisons of various media have been made by Cook (*Soil Sci.*, 1916, 1, 153-161). The more uniform the results the better the medium.

to justify the assumption that the two phenomena are causally connected. Two cases have, however, been studied where no such relationship exists.

(1) The soil treatment, while raising the total numbers, has either acted differentially on the organisms and did not encourage the ammonia producers to develop, or it has caused them to effect some decomposition that does not give rise to ammonia. (See p. 186.) The addition of certain organic compounds to the soil has this effect (Table LXIX.).

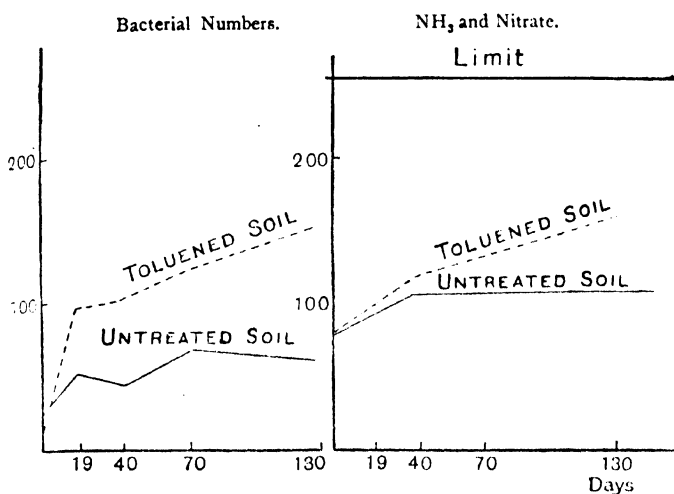
TABLE LXIX.—EFFECT OF CERTAIN ORGANIC SUBSTANCES ON BACTERIAL NUMBERS AND ON NITRATE PRODUCTION.

| Substance Added. | Bacterial Numbers After 50 Days (millions per grm.). | | Ammonia and Nitrate Present After 50 Days. | | Observers. |
|--------------------------------------|--|------------------------|--|------------------------|--|
| | In Control Soil. | In Treated Soil. | In Control Soil. | In Treated Soil. | |
| Cane sugar (0.25 per cent.) | 21 | 51 | 32 | 20 | Russell and Hutchinson (246a) Buddin (64a) " " |
| Amyl alcohol (0.1 per cent.) | 30 | 85 | 37 | 35 | |
| Phenol (M/200 per kilo) ¹ | 27 | 101 | 30 | 33 | |
| Hydroquinone (M/200 per kilo) | 16 | 55 | 35 | 44 | |

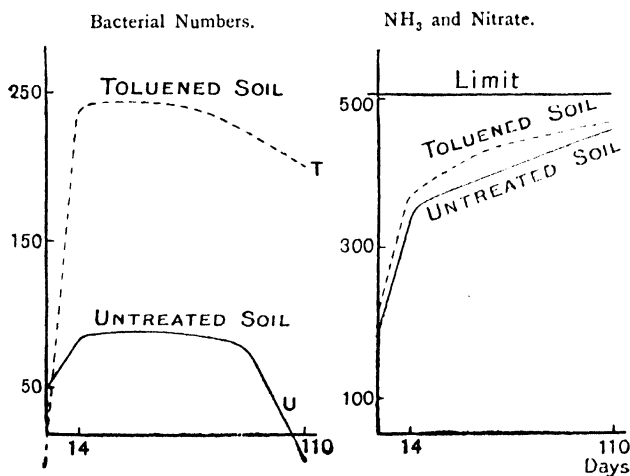
(2) Even when the ammonia-producing organisms are caused to multiply they do not increase the stock of ammonia and nitrates in the soil beyond a certain limiting amount. Thus partial sterilisation increases bacterial numbers and usually increases the amount of ammonia and nitrate also, but it fails to do this after a certain quantity has accumulated (Fig. 24).

On looking over the figures in Tables LXVII. and LXVIII. (p. 262) it is evident that the numbers of bacteria revealed by this method bear no relationship to the amount of crop growth. Other field experiments have given similar results. Yet in laboratory and pot experiments bacterial counts have often

¹ See p. 212.



Case 1.—Small amounts of NH₃ and nitrate initially present. A relationship is indicated between bacterial numbers and the rate of production of NH₃ and nitrate.



Case 2.—Large amounts of ammonia and nitrate initially present. No relationship like that in Case 1 is indicated.

FIG. 24.—Relation between bacterial numbers and amounts of nitrate and ammonia formed.

proved most valuable; numerous instances are given in the Rothamsted papers on soil sterilisation (241).

This discrepancy between field and laboratory experience is cleared up by a closer examination of the nature of the relationship between bacterial activity and plant growth. The connection, as already pointed out, lies in the fact that bacteria decompose the organic matter of the soil and make new plant food out of old plant residues. If the factor limiting plant growth happens to be the supply of nitrogenous plant food or the rate of decomposition of the plant residues we may expect to find a close connection between bacterial activity and soil fertility; if, on the contrary, the limiting factor is something else—such as water supply, lack of phosphates, etc.—no such connection is necessary. Even here, however, a connection may exist, for bacteria are living things, affected by the same circumstances that influence plants.

Three distinct cases, therefore, arise :—

(1) Bacterial activity may show no sort of relationship with soil fertility, because fertility is limited by some factor other than the nitrogen supply or rate of decomposition of plant residues.

(2) Bacterial activity may be directly related to soil fertility but the relationship is only accidental, both bacteria and plants being affected by the same limiting factor.

(3) Bacterial activity may be directly related to soil fertility and the relationship is causal, fertility being limited by the amount of ammonia and nitrate produced by the bacteria or by other decompositions which they effect.

Instances of the first are common in arid and semi-arid districts.

The second case is not unfrequent. An admirable illustration is afforded by the experiments of Crowther and Ruston on the effect of acid rain-water on plant growth (71). The pots were watered with solutions of sulphuric acid, some being of the same order of concentration as the Leeds rain-water. The acid depressed the growth not only of plants but of bacteria also, and the effect is very similar in both cases (Table LXX.).

TABLE LXX.—EFFECT OF ACIDULATED WATER ON THE GROWTH OF PLANTS AND BACTERIA. CROWTHER AND RUSTON (71).

| | Crop Yields Dry Matter, Grms. | Ammonifying Power. | Nitrifying Power. | Nitrogen Fixing Power. | Bacterial Numbers, Millions per gm. | Oxygen Absorption, mm. | Ammonia and Nitrate left in Soil at end of Experiment per million. |
|--|-------------------------------|--------------------|-------------------|------------------------|-------------------------------------|------------------------|--|
| Soil watered with Garforth rain-water, neutralised | 14.7 | 13.9 | 1.02 | 4.6 | 5.2 | 12 | 9.3 |
| 1 part H ₂ SO ₄ per 100,000 | 12.0 | 12.1 | 0.80 | 3.3 | 1.3 | 8 | 6.2 |
| 2 " " " | 8.0 | 11.2 | 0.85 | 3.0 | 1.1 | 6 | 8.2 |
| 4 " " " | 3.9 | 10.5 | 0.52 | 2.8 | 0.7 | 4 | 8.1 |
| 8 " " " | 3.7 | 10.3 | 0.36 | 2.4 | 0.1 | 4 | 8.4 |
| 16 " " " | nil | 10.3 | 0.28 | 1.9 | 0.04 | 3 | 8.1 |
| 32 " " " | nil | 8.1 | 0.13 | 1.8 | 0.015 | 0 | 9.4 |

At first sight this looks like a close relationship between bacterial activity and plant growth. But the figures in the last column show that the failure of the crop is not due to the failure of the bacteria to produce ammonia and nitrate, for relatively large amounts of these substances are left at the end of the experiment.

In similar manner the growth both of bacteria and of plants may be helped by the same cause. This is more fully discussed in the following section. Speaking generally, it is found that the bacterial numbers increase as the intensity of the farming increases. Thus Stoklasa and Ernest (273*a*) found only 1 to 2 million organisms per gm. in their barley land, 3 to 5 millions on the better treated sugar-beet land, and 7 to 8 millions on the clover land. Again, the addition of plant residues or of farmyard manure to the soil increases the bacterial numbers by furnishing the organisms with additional food;¹ it also increases the crop. Moorland soils contain only few bacteria and are very unsuited to the growth of most plants. But after cultivation and treatment with lime and manures they become much better media both for plants and bacteria. Fabricius and von Feilitzen (97*b*) found

¹ Examples are given by P. E. Brown, *Iowa Research Bull.*, No. 13, 1913, and by Heinze, *Landw. Jahrbücher*, 1910, 39; *Ergänz. Bd.* 3, 314-343.

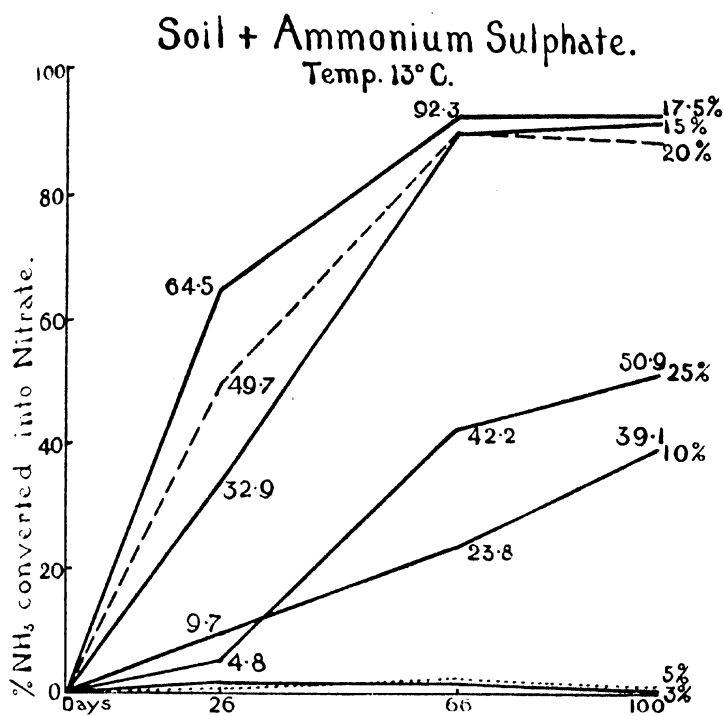
0.1 million of bacteria per grm. in the raw moorland soil, but 7 millions in similar soil that had been cultivated and manured.

So close is the similarity between ordinary crops and azotobacter in relation to soil acidity that an azotobacter test is used in Denmark for determining the need of lime (p. 242).

It may often be difficult in practice to determine whether the relationship between the bacterial numbers and plant growth is causal or accidental, but the principle is perfectly clear; the relationship is causal only when the plant growth is limited by the supply of compounds produced by bacterial activity, or the rate at which plant residues or harmful substances such as phenol, thiocyanates, etc., are decomposed by bacteria. The recognition of this central principle greatly facilitates investigation, for it shows the futility of haphazard attempts to correlate bacterial activity and plant growth over a set of soils that are not strictly comparable. The better course is to narrow down the problem and confine it to the elucidation of the connection between bacterial activity and nitrate production.

Effect of Soil Conditions on Bacterial Numbers and on Nitrate Production.

On general grounds it might be expected that the soil bacteria would be affected by external conditions in much the same way as plants, and to a considerable extent this happens. Most of the effects observed with growing plants have been paralleled in the case of the soil bacteria. There are, however, nearly always differences between the effects produced on the bacterial numbers and on the amount of work done: one may be increased but not the other. Discussion of the effects of external conditions on bacterial numbers is much hampered by the paucity of data. Observers have often been content to make counts once in twenty or thirty days, and they have usually assumed that changes in numbers are slow. Cutler and Crump have shown (73c) that this supposition is unfounded: changes proceed rapidly from day to day.



Additional Nitrate found in Soil alone.
(Loam Göttingen)
Temp. 13° C.

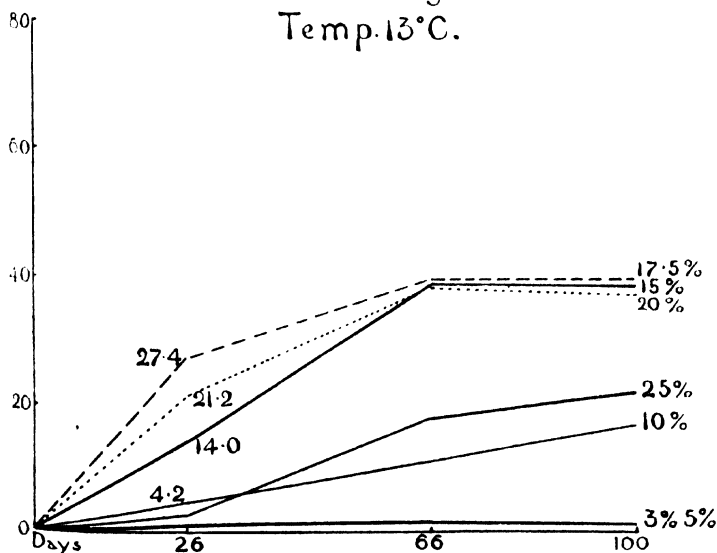


FIG. 25.—Effect of moisture on nitrification process in the soil (Traaen).

Inspection of their curves shows that reliable conclusions cannot be drawn when counts are taken at long intervals.

Effect of Temperature.—Bacteria being living organisms it is natural to expect that their activity increases with the temperature up to a certain point. The amount of nitrate does show this expected increase but the bacterial numbers do not, there being no steady rise as the temperature of storage increases (Table LXXI.). Field observations lead to the same conclusion (p. 275).

TABLE LXXI.—EFFECT OF TEMPERATURE OF STORAGE ON BACTERIAL NUMBERS AND NITRATE PRODUCTION. RUSSELL AND HUTCHINSON (241a).

| Temperature of Storage. | Bacteria, Millions per Grm. of Dry Soil. | | | Nitrate and Ammonia, Parts per Million of Dry Soil. | | |
|-------------------------|--|----------------|----------------|---|----------------|----------------|
| | At Start. | After 10 Days. | After 50 days. | At Start. | After 10 Days. | After 50 days. |
| 7°-12° | 16 | 16 | 16 | 17 | 18 | 22 |
| 20° | | 12 | 21 | | 16 | 30 |
| 30° | | 15 | 14 | | 24 | 36 |
| 40° | | 9 | 14 | | 55 | 76 |

Effect of Moisture.—Increasing moisture supply causes increases in bacterial numbers, but they are not regular (241c). Field observations give the same result (p. 275). The rate of nitrate production increases up to a certain point, beyond which it decreases, presumably because of the lack of air. Traaen's results are plotted in Fig. 25.¹ On the practical side it is found that application of irrigation water in arid regions has a distinctly beneficial effect on the ammonifying and nitrifying powers, both of cropped and fallow soils, and on the numbers of organisms on fallow soils. Excess of water, however, washes out the resulting nitrate from the soil and so deprives the plant of the advantage it would otherwise gain. (J. E. Greaves, R. Stewart, and C. T. Hirst (113b).)

Effect of Added Organic Matter.—As shown on p. 252 the

¹ *Centr. Bakt. Par.*, 1916, 45, 119. Other results are plotted in Greaves and Carter's paper (113d), where also a full bibliography is given.

effect of added organic matter is to increase supplies of energy and therefore to increase bacterial numbers. The question whether nitrate supplies will be increased depends on the proportion of nitrogen present in the added matter: if it is rich in nitrogen a considerable amount of nitrate may be formed;¹ if it contains no nitrogen there arises an actual loss of nitrate though there may be a fixation of gaseous nitrogen. The special case of farmyard manure has been much studied.²

Effects of Lime, Calcium Carbonate, and Magnesium Carbonate.—Numerous papers have been written on this subject and the results are at first sight somewhat contradictory. Much of the work has been done on acid soils, where, as might be expected, benefit has been derived from neutralisation. F. E. Bear³ finds that calcium carbonate greatly increases the numbers of bacteria in acid soils once the neutral point is passed, but not before: it much increases ammonification and nitrification up to the neutral point, but to a less extent afterwards. In neutral soils, however, less concordant results have been obtained; some investigators have observed detrimental effects from further addition of calcium carbonate,⁴ while others have obtained only beneficial results,⁵ bacterial numbers, ammonifying power and nitrifying power all being increased. Magnesium carbonate may be more effective than calcium carbonate in small quantities, but it is toxic in larger amounts.⁶ Lime in excess of a certain amount acts as a sterilising agent (139c).

¹ For the effect of the N : C ratio see P. E. Brown and F. E. Allison, *Soil Sci.*, 1916, **1**, 49-75; and also H. B. Hutchinson and J. Clayton (139f).

² P. 193, also T. G. Temple, *Georgia Rpt.*, 1916; Greaves and Carter, *Journ. Ag. Res.*, 1916, **6**, 883.

³ *Soil Sci.*, 1917, **4**, 433.

⁴ E.g. J. G. Lipman, P. E. Brown, and I. L. Owen, *Centr. Bakt. Par.*, 1911, **30**, 156-181.

⁵ S. S. Peck, *Hawaiian Sugar Planters' Chem. Bull.*, 34, 1911; P. E. Brown, *Iowa Research Bull.*, 2, 1911; *Bull.*, 44, 1918; J. E. Greaves, *Soil Sci.*, 1916, **2**, 443-480; H. L. Fulmer, *Journ. Agric. Res.*, 1918, **12**, 463-504, although he obtained harmful effects on nitrification.

⁶ J. G. Lipman and P. E. Brown, *N. J. Agric. Expt. Sta. 28th Ann. Rept.*, 141-204; C. B. Lipman and P. S. Burgess, *Journ. Agric. Sci.*, 1914, **6**, 484-498; H. L. Fulmer, *Journ. Ag. Res.*, 1918, **12**, 463.

*Effect of Salts.*¹—Alkali salts adversely affect bacteria somewhat as they do green plants: in India a sufficient degree of similarity exists to allow the wheat-yielding power of an alkali soil to be estimated from such bacterial activities as CO₂ production, ammonification, etc.² The problem has been much investigated in the Western United States where alkali salts are apt to cause trouble. Systematic investigations have been made by C. B. Lipman in California (175*b*) and by J. E. Greaves and his co-workers in Utah (113). Typical results are given in Table LXXII. The ammonifying organisms are usually stimulated by small concentrations of "alkali salts" but adversely affected by larger ones, though they are less susceptible than wheat seedlings. The effect is not constant but varies with differences in soil and conditions.³ As a general rule chlorides are the most toxic salts, while nitrates, sulphates, and carbonates are successively less toxic; it is suggested that the electronegative ion plays the more important part (113). Nitrifying organisms, however, are more susceptible than ammonia producers and the effects are determined by the specific compound rather than by one ion. There is also a well-marked antagonism of ions (*e.g.* Ca and K; Mg and Na; K and Na; (Na₂)CO₃ and (Na)Cl)⁴ as in the case of green plants (p. 79). Salts of arsenic,⁵ copper,⁶ lead, zinc, and iron appear to be capable, in suitable concentration, of stimulating nitrifying organisms but not ammonification. Nutritive salts have a marked effect. Phosphates notably increase all types of bacterial activity in the soil:⁷ potassium salts have acted well in

¹ For a summary of the extensive literature see J. E. Greaves, *Soil Sci.*, 1916, 2, 443-480.

² J. H. Barnes and Barkat Ali, *Ag. Journ. India*, 1917, 12, 368.

³ W. P. Kelley, *Journ. Agric. Research*, 1916, 7, 417-437.

⁴ C. B. Lipman, *Bot. Gaz.*, 1909, 48, 106, and *Centr. Bakt. Par.*, 1914, 41, 430-444 (with P. S. Burgess); see also J. E. Greaves, *Soil Sci.*, 1920, 10, 77-102.

⁵ J. E. Greaves, *Science*, 1917, p. 204.

⁶ C. B. Lipman and P. S. Burgess, *Univ. Cal. Pub. Agric. Sci.*, 1914, 1, 127-139.

⁷ E. B. Fred and E. B. Hart, *Wisconsin Research Bull.*, 35, 1915; and *Centr. Bakt. Par.*, 11, 1916, 45, 379; G. P. Koch, *Journ. Biol. Chem.*, 1917, 31, 411; see also p. 203.

certain soils,¹ but not on all. Nitrates increase the amount of ammonification,² the growth of the organisms causing decay (176*a*), the nitrogen fixing azotobacter (p. 199) and of nitrate assimilating organisms (113*c*), though in higher quantities they become toxic.

TABLE LXXII.—PERCENTAGES OF VARIOUS SALTS IN LOAM SOIL WHICH ARE NECESSARY TO REDUCE AMMONIFICATION, GERMINATION AND DRY MATTER PRODUCED IN WHEAT TO ABOUT HALF NORMAL. J. E. GREAVES, E. G. CARTER, AND H. C. GOLDTHORPE (113*a* AND *c*).

| | Wheat Seedling to Half Normal. | Ammonification to Half Normal. | Nitrification to Half Normal. |
|------------------------|-----------------------------------|-----------------------------------|----------------------------------|
| Sodium chloride . . | 0'20 | 0'117 | 0'234 |
| Calcium " . . | '30 | '222 | — |
| Potassium " . . | '25 | '298 | '298 |
| Magnesium " . . | '40 | '381 | '006 |
| Potassium nitrate . . | '40 | '607 | '101 |
| Sodium " . . | '30 | '850 | '170 |
| " sulphate . . | '55 | '852 | '568 |
| Magnesium " . . | '70 | '963 | '361 |
| Sodium carbonate . . | '30 | 1'166 | '212 |
| Magnesium nitrate . . | '45 | 1'187 | '074 |
| Potassium sulphate . . | '60 | 1'394 | '349 |
| " carbonate . . | '70 | 1'520 | '138 |

Effect of Dissolved Oxygen Supply.—Russell and Appleyard (241*g*) found that rainfall has a more definite effect than moisture in increasing bacterial numbers and biochemical changes in the soil. They attribute this action to the oxygen dissolved in the rain-water which renews the dissolved atmosphere in the soil and gives the organisms a new lease of activity.

Effect of Previous Treatment of the Soil.—Prolonged drought affects the soil even after it has passed away and the soil has become moistened. The rate of production of nitrate and the bacterial numbers both increase (24*c* and also Prescott³).

Field Observations.—The general phenomena observed in the laboratory can be seen also in the field, but it is less easy to disentangle the various factors.

¹J. Dumont, *Compt. Rend.*, 1897, 125, 469-472.

²D. A. Coleman, *Soil Sci.*, 1917, 4, 345.

³A note on the Sheraqi soils of Egypt (*Journ. Ag. Sci.*, 1920, 10, 177.)

As in the laboratory experiments (p. 272) the bacterial numbers show no relation to the temperature and moisture content of the soil. Numerous counts were made by Hiltner and Störmer (135*c*) from plots of cropped ground, and of unmanured and dunged fallows. Some of these are recorded in Table LXXIII.

TABLE LXXIII.—BACTERIA IN CROPPED AND FALLOW SOILS, MILLIONS PER GRAM. HILTNER AND STÖRMER (135*c*).

| | 1901. | | | 1902. | | |
|--------------------------------|---------|---------|---------|--------|----------|---------|
| | 10 May. | 27 Aug. | 18 Oct. | 1 Feb. | 12 June. | 18 Aug. |
| Cropped land, grass and clover | 8.3 | 3.2 | 6.4 | 6.6 | 8.1 | 4.9 |
| Cultivated fallow, unmanured. | 8.0 | 4.2 | 4.0 | 4.1 | 5.7 | 4.1 |
| " " dunged ¹ | 11.0 | 10.5 | 11.0 | 9.3 | 7.2 | 8.4 |

The only marked effect is that of the dung; the net result of the clover and grass has only been small in spite of the organic residues shed by the roots. On no plot has the warm summer weather increased the bacterial numbers.

Later on Engberding (94) made a more extensive series of counts of the bacteria in plots of ground under known treatment and published his results in very complete form, giving details of temperature, moisture content, etc. Here again no connection could be traced between temperature or moisture content and bacterial numbers. A very similar result was obtained by W. E. King and Doryland (148). Neither temperature nor moisture changes explained the observed fluctuations in bacterial numbers.²

Some of Waksman's results (292*a*) with a garden soil at New Jersey are given in Table LXXIV.

Russell and Appleyard (241*g*) have studied the problem in some detail at Rothamsted, and have determined the bacterial numbers, and the nitrate in the soil, and the amount

¹ Dung applied in July at the rate of 130 to 140 Centner pro Morgen (10 to 11 tons per acre).

² In these experiments, however, one cubic millimetre only of the soil suspension was used for the plate cultures.

of CO_2 in the soil air, at frequent intervals for a period of two seasons on several of the plots. The experimental data do not represent the amounts of production but only of accumulation; nevertheless the curves are found to give useful information as to production.

TABLE LXXIV.—BACTERIA IN GARDEN SOIL, NEW JERSEY, MILLIONS PER GRAM. WAKSMAN (1924).

| Date of Sampling | 1915 Jan. 30. | Feb. 12. | Mar. 1. | Mar. 23. | Apr. 16. | May 8. | June 3. | July 7. | Aug. 8. | Sept. 10. | Oct. 2 | Nov. 30 ¹ | 1916. Jan. 4. |
|---|------------------|----------|---------|----------|----------|--------|---------|---------|---------|-----------|--------|----------------------|------------------|
| Nos. of bacteria, millions per gram. | 8.7 | 6.0 | 8.8 | 4.3 | 10.7 | 4.8 | 6.9 | 7.8 | 5.0 | 8.8 | 5.9 | 6.9 | 9.2 |
| Moisture content, per cent. | 15 | 14 | 13 | 8 | 9 | 9 | 9 | 9 | 12 | 10 | 9 | 9 | 19 |

These figures are for the top inch: samples were taken at six different depths with similar results.

In the first instance it is observed that the curves are all sufficiently alike to justify the view that in the soil, as in the laboratory, the phenomena of nitrate production and CO_2 evolution are closely related to the numbers of bacteria. When the bacterial numbers rise there is a rise in the amount of CO_2 and of nitrate. But the nitrate curve does not sharply agree with the others: it is displaced, showing a lag of two or three weeks.

The general results are illustrated by the curves in Fig. 26. During the winter months there is very little activity. But as soon as the temperature rises above 5°C . change sets in: bacterial numbers, CO_2 ,¹ and nitrates all increase. The rise, however, is not long sustained; it is followed by a fall, notwithstanding the continuance of favourable temperature conditions. To some extent this is due to lack of moisture, for the curves now begin to resemble the soil moisture curves. It is also due to lack of something supplied by rain—presumably dissolved oxygen—for the rainfall curves more closely fit the CO_2 and bacterial number curves. This period of summer

¹ The very sharp rise of CO_2 in May and August appears to be associated with the crop (241g).

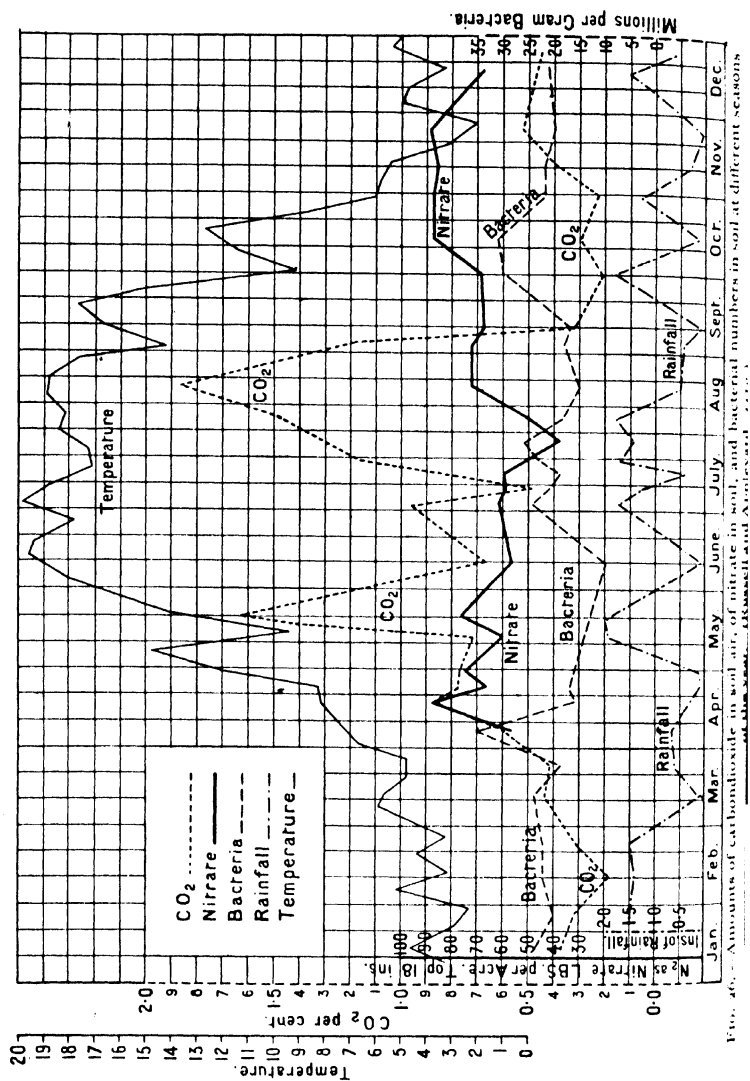


FIG. 46. Amounts of carbon dioxide in soil air, of nitrate in soil, and bacterial numbers in soil at different seasons of the year. (Hewell and Ainsworth 1933)

sluggishness is followed by one of considerable activity in autumn and this in turn by the period of winter inertness. The growing crop appears to affect the biochemical changes (p. 296).

These periods of spring activity, summer sluggishness, and autumn activity seem to be fairly general, and they have been recorded elsewhere.

Using Remy's method of physiological grouping Löhnis and Sabaschnikoff at Leipzig (181*e*) obtained a curious and wholly unexpected set of curves suggesting some remarkable seasonal relationships. The urea-decomposing power, nitrifying power, nitrogen-fixing power, and to a less extent the denitrifying power, all reached a maximum in spring, a minimum in summer and a maximum again in September. Müntz and Gaudechon (209) also showed by a somewhat different method that the nitrifying power is at a maximum in spring. Conn (70) obtained a similar curve for the bacterial numbers in his plots: the numbers of bacteria being high in February when the land was frozen, they fell in summer but rose again in autumn (Fig. 27). Brown and Smith at Iowa (60*d*) also found the highest numbers in frozen soils, but Wojtkiewicz (314), on the other hand, found the maximum later on in spring, the winter numbers being much lower.

Leather (167*b*) and Jensen (144) have obtained parallel results for the amount of nitrate in the soil.

Reviewing the whole of the preceding results, it seems clear that in normal soils we are dealing with something more than a bacterial population. The seasonal fluctuations may represent some deep-seated phenomenon: seasonal fluctuations also occur in the plankton of the sea.¹ But the erratic results obtained with changes in temperature and moisture suggest that other organisms are also present interfering with the activity of the soil bacteria. This view arose out of the work on partial sterilisation which revealed the presence of

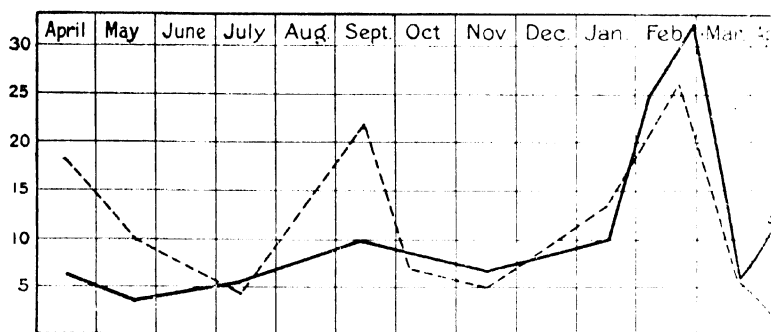
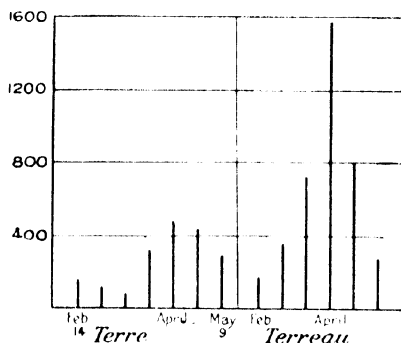
¹ See W. A. Herdman, *Pres. Address Brit. Ass.*, 1920.

another great group of organisms, and which we must now proceed to discuss.

Investigation on the Partial Sterilisation of the Soil.

The earliest observations that soil is altered by an apparently inert antiseptic arose out of attempts to kill insect

Le Réveil de la Terre (Müntz and Gauduchon)
Rate of Nitrification.



Bacterial numbers in soil: plots 1B and 4B. Cropped with millet: unmanured. (The curve showing moisture content is very similar to that for 4B.) (Conn.)

FIG. 27.—Bacterial activity in soils at different seasons of the year.

pests in the soil by means of carbon disulphide. This substance, which for fifty years has been known as an insecticide, was used in 1877 by Oberlin,¹ an Alsatian vine-grower.

¹ *Boden-Mudigkeit und Schwefelkohlenstoff*, Mainz, 1894.

to kill phyloxera, and by Girard¹ in 1887 to clear a piece of sugar-beet ground badly infested with nematodes. In both cases the subsequent crops showed that the productiveness of the soil had been increased by the treatment.

The first piece of scientific work came from A. Koch in 1899 (151*a*), who, working with varying quantities of carbon disulphide, concluded that it stimulates the plant root to increased growth. Four years later Hiltner and Störmer (135*c*) showed that the bacterial flora of the soil undergoes a change. The immediate effect of the antiseptic was to decrease by about 75 per cent. the number of organisms capable of developing on gelatin plates; then as soon as the antiseptic had evaporated, the numbers rose far higher than before, and there was also some change in the type of flora. It was argued that the increased numbers of bacteria must result in an increased food supply for the plant, and it was claimed that the new type of flora was actually better than the old, in that denitrifying organisms were killed, nitrogen-fixing organisms increased, and nitrification only suspended during a period when nitrates were not wanted and might undergo loss by drainage. In a later publication Hiltner (135*d*) shows that other volatile or easily decomposable antiseptics produce the same effect. The important part of this work is unquestionably the discovery that the organisms in the treated soils ultimately outnumber those in the original soil.² The hypothesis that the new type of flora is actually more efficient than the old rests on less trustworthy evidence, and has indeed been modified in some of its details by Hiltner himself.

The effect of heat on the productiveness of the soil was first noticed by the early bacteriologists. It had been assumed that heat simply sterilised the soil and produced no other change, until Frank (100) in 1888 showed that it increased

¹ *Bull. Soc. Nat. d'Agric.*, 1894, 54, 356.

² Sewage investigators have found that the disinfection of sand filters leads to increases in the numbers of bacteria. This was observed in the typhoid epidemic at Lincoln in 1904 and also in the experimental sewage filter at Guildford in 1907 (Houston and McGowan, *Fifth Report, Sewage Commission*, Appendix 4, Cd. 4282, 1910, p. 111).

the soluble mineral and organic matter and also the productiveness. Later work by Pfeiffer and Franke (224*b*) and by Krüger and Schneidewind (156*a*) showed that plants actually take more food from a heated than from an unheated soil. Heat undoubtedly causes decomposition of some of the soil constituents, quite apart from its effect on the soil flora; it also produces physical effects;¹ all these actions probably play a part in determining the increased productiveness of heated soils.

Other explanations of the effects of partial sterilisation have been put forward. Pickering (226*b*) finds that the amount of soluble matter in the soil is increased by treatment with volatile antiseptics. Greig Smith supposes that soils contain a harmful waxy material which he calls "agricere" and which he supposes to be removed during partial sterilisation. Russell and Hutchinson were unable to confirm this at Rothamsted, nor could J. P. du Buisson at Cornell, who found that extraction with volatile antiseptics gave no better results than addition of liquid and subsequent evaporation.² Bolley supposes that soils normally contain parasitic fungi which are destroyed by partial sterilisation. Russell and Hutchinson (241*c*) consider that the soil population is complex and that some of its numbers act detrimentally on the bacteria which produce plant nutrients: these detrimental forms are more readily killed than the useful bacteria, with the result that the new population produces more ammonia and nitrate than the old one. The detrimental organisms are provisionally identified with protozoa (p. 288).

It is agreed by all who have seriously studied the subject that the effects produced by partial sterilisation are complex: several factors operate simultaneously. In consequence, a particular factor cannot be regarded as established until its operation has been proved by some wholly independent

¹ For chemical effects see 241*b* and also Pickering, *Journ. Ag. Sci.*, iii., 171-178; Seaver and Clark, *Biochem. Bull.*, 1912, 1, 413; and Schreiner and Lathrop, U.S. Dept. of Ag. Bureau of Soils, *Bull.* 89, 1912. For physical effects see Czermak, *Landw. Versuchs-Stat.*, 1912, 76, 75.

² *Soil Sci.*, 3, 353-392.

method. There has been much discussion of the view expressed by Russell and Hutchinson, and many investigators, e.g. J. M. Sherman (261), do not admit the presence of any biological factor in soils detrimental to bacteria. The evidence in favour of the view will therefore be set out in some detail.

The writer's investigation on this subject began in the first instance as the result of an accident. In virtue of its large population of micro-organisms soil absorbs a considerable quantity of oxygen, and evolves a corresponding amount of carbon dioxide. An experiment had been arranged to demonstrate the well-known fact that soil heated to 130° C., and therefore completely devoid of micro-organisms, lost much of its power of absorbing oxygen. By an accident the autoclave was not available; the soil was therefore heated only in the steam oven, and it gave the remarkable result that its power of absorbing oxygen instead of falling, as was expected, considerably increased. Now the steam did not kill all the organisms, but spared those capable of forming spores; *i.e.* sterilisation was only partial. Partial sterilisation by means of volatile antiseptics gave the same result. The conclusion was drawn that partial sterilisation increased the bacterial activity, and consequently the amount of decomposition. The increased quantity of plant food thus formed is shown by the amounts taken up by the plant. Table LXXV. contains a typical series of results.

Further investigations by Russell and Hutchinson (240c) led to the following conclusions:—

(1) Partial sterilisation of soil, *i.e.* heating to a temperature of 60° C. or more, or treatment for a short time with vapours of antiseptics, such as toluene, causes first a fall then a rise in bacterial numbers. The rise sets in soon after the antiseptic has been removed and the soil conditions are once more favourable for bacterial development; it goes on till the numbers considerably exceed those present in the original soil.

(2) Simultaneously there is a marked increase in the rate of accumulation of ammonia. This sets in as soon as the

bacterial numbers begin to rise, and the connection between the two quantities is normally so close as to indicate a causal relationship; the increased ammonia production is, therefore, attributed to the increased numbers of bacteria. There is no disappearance of nitrate; the ammonia is formed from organic nitrogen compounds.

TABLE LXXV.—WEIGHT AND COMPOSITION OF CROPS GROWN ON PARTIALLY STERILISED SOILS. RUSSELL AND DARBISHIRE (2406).

| | Dry Weight of Crop. | Percentage Composition of Dry Matter. | | | Weight of Nutrients Taken by the Plant from Soil, grms. | | |
|---|---------------------|---------------------------------------|---------------------------------|-------------------|---|---------------------------------|-------------------|
| | Grms. | N. | P ₂ O ₅ . | K ₂ O. | N. | P ₂ O ₅ . | K ₂ O. |
| Buckwheat. | | | | | | | |
| Untreated soil | 18.14 | 2.75 | 1.87 | 5.62 | .499 | .339 | 1.019 |
| Soil treated with carbon disulphide | 23.27 | 3.15 | 2.34 | 5.97 | .733 | .544 | 1.389 |
| Mustard. | | | | | | | |
| Untreated soil | 15.88 | 2.30 | 1.00 | 4.20 | .367 | .159 | .68 |
| Heated soil | 24.33 | 4.43 | 2.08 | 5.02 | 1.077 | .506 | 1.221 |

These conclusions are generally accepted.

TABLE LXXVI.—AMMONIA AND NITRATE ACCUMULATING IN A SOIL KEPT TWENTY-THREE DAYS AT ABOUT 15° C. IN A MOIST CONDITION, PARTS PER MILLION OF DRY SOIL.

| | Nitrogen Present as Ammonia. | | Nitrogen Present as Nitrates. | | Total Nitrogen Present as Ammonia and Nitrate. | | |
|--|------------------------------|----------------|-------------------------------|----------------|--|----------------|------------------|
| | At Beginning. | After 23 Days. | At Beginning. | After 23 Days. | At Beginning. | After 23 Days. | Gain in 23 Days. |
| Untreated soil | 1.8 | 1.7 | 12 | 16 | 13.8 | 17.7 | 3.9 |
| Soil heated 2 hours to 98° C. | 6.5 | 43.8 | 13 | 12 | 19.5 | 55.8 | 36.3 |
| Soil treated with toluene, which was then evaporated | 5.0 | 27.8 | 12 | 12 | 17.0 | 39.8 | 22.8 |
| Soil treated with toluene, which was not removed | 7.2 | 14.5 | 11 | 10 | 18.2 | 24.5 | 6.3 |

(3) The increase in bacterial numbers is the result of improvement in the soil as a medium for bacterial growth

and not an improvement in the bacterial flora. Indeed, the new flora *per se* is less able to attain high numbers than the old. This is shown by the fact that the old flora when re-introduced into partially sterilised soil attains higher numbers and effects more decomposition than the new flora. Partially sterilised soil plus 0.5 per cent. of untreated soil soon contains higher bacterial numbers per gram. and accumulates ammonia at a faster rate than partially sterilised soil alone.

(4) The improvement in the soil brought about by partial sterilisation is permanent, the high bacterial numbers being kept up even for 200 days or more.¹ The improvement, therefore, did not consist in the removal of the products of bacterial activity, because there is much more activity in partially sterilised soil than in untreated soil. Further evidence is afforded by the fact that a second treatment of the soil some months after the first produces little or no effect.

It is evident from (3) and (4) that the factor limiting bacterial numbers in ordinary soils is not bacterial, nor is it any product of bacterial activity, nor does it arise spontaneously in soils.

(5) But if some of the untreated soil is introduced into partially sterilised soil, the bacterial numbers, after the initial rise (see (3)), begin to fall. The effect is rather variable, but is usually most marked in moist soils that have been well supplied with organic manures; *e.g.* in dunged soils, greenhouse soils, sewage farm soils, etc. Thus the limiting factor can be reintroduced from untreated soils.

This is controverted by J. M. Sherman at Wisconsin (261), who failed to find any evidence that the introduction of untreated soil brought down the bacterial numbers in partially sterilised soil.

(6) Evidence of the action of the limiting factor in untreated soils is obtained by studying the effect of temperature on

¹ Subsequent work indicates that a rapid and considerable rise followed by a fall takes place in the first few days after treatment with certain antiseptics. This is attributed to the utilisation by certain organisms of the trace of antiseptic left in the soil; it is regarded by the writer as distinct from the sustained but lower rise referred to here.

bacterial numbers. Untreated soils were maintained at 10°, 20°, 30° C., etc., in a well-moistened aerated condition, and periodical counts were made of the numbers of bacteria per grm. Rise in temperature rarely caused any increase in bacterial numbers; sometimes it had no action, often it caused a fall. But after the soil was partially sterilised the bacterial numbers showed the normal increase with increasing temperatures. Similar results were obtained by varying the amount

TABLE LXXVII.—EFFECT OF TEMPERATURE OF STORAGE ON BACTERIAL NUMBERS IN SOILS, MILLIONS PER GRAM.

| Temperature of Storage °C. | Untreated Soil. | | | | Soil Treated with Toluene. | | | |
|----------------------------|-----------------|----------------|----------------|----------------|----------------------------|----------------|----------------|----------------|
| | At Start. | After 13 Days. | After 25 Days. | After 70 Days. | At Start. | After 13 Days. | After 25 Days. | After 70 Days. |
| 5°-12° | 65 | 63 | 41 | 32 | 8.5 | 73 | 101 | 137 |
| 20° | 65 | 41 | 22 | 23 | 8.5 | 187 | 128 | 182 |
| 30° | 65 | 27 | 50 | 16 | 8.5 | 197 | 145 | 51 |
| 40° | 65 | 14 | 9 | 33 | 8.5 | 148 | 52 | 100 |

of moisture but keeping the temperature constant (20° C.). The bacterial numbers in untreated soil behave erratically and tended rather to fall than to rise when the conditions were made more favourable to trophic life; on the other hand, in partially sterilised soil, the bacterial numbers steadily increased with increasing moisture content. Again, when untreated soils are stored in the laboratory or glass-house under varying conditions of temperature and of moisture content the bacterial numbers fluctuate erratically; when partially sterilised soils are thus stored the fluctuations are regular.

(7) When the curves obtained in (6) are examined it becomes evident that the limiting factor in the untreated soils is not the lack of anything¹ but the presence of something active.

(8) This factor, as already shown, is put out of action by antiseptics and by heating the soil to 60° C., and once out of

¹ The soils included fertile loams well supplied with organic matter, calcium carbonate, phosphates, etc.

action it does not reappear. Less drastic methods of treating the soil put it out for a time, but not permanently: *e.g.* heating to 50°, rapid drying at 35°, treatment with organic vapours less toxic than toluene (*e.g.* hexane), incomplete treatment with toluene. In all these cases the rise induced in the bacterial numbers per gram. is less in amount than after toluene treatment and is not permanent; the factor sets up again. As a general rule, if the nitrifying organisms are killed the limiting factor is also extinguished; if they are only temporarily suppressed the factor also is only put out for a time.

(g) The properties of the limiting factor are:—

(a) It is active and not a lack of something (see (7)).

(b) It is not bacterial (see (3) and (4)).

(c) It is extinguished by heat or poisons, and does not reappear if the treatment has sufficed to kill sensitive and non-spore-forming organisms; it may appear, however, if the treatment has not been sufficient to do this.

(d) It can be reintroduced into soils from which it has been permanently extinguished by the addition of a little untreated soil.

(e) It develops more slowly than bacteria, and for some time may show little or no effect, then it causes a marked reduction in the numbers of bacteria, and its final effect is out of all proportion to the amount introduced.

(f) It is favoured by conditions favourable to trophic life in soil, and finally becomes so active that the bacteria become unduly depressed. This is one of the conditions obtaining in glass-house "sick" soils.¹

It is difficult to see what agent other than a living organism can fulfil these conditions. Search was therefore made for larger organisms capable of destroying bacteria, and considerable numbers of protozoa were found. Active ciliates and amoebæ are killed by partial sterilisation. Whenever they are killed the detrimental factor is found to be put out of action,

¹ This is dealt with fully in *Journ. Agric. Sci.*, vol. 5, pp. 27-47, 86-111 (1912).

the bacterial numbers rise and maintain a high level. When-
ever the detrimental factor is not put out of action the protozoa
are not killed. To these rules we have found no exception.

TABLE LXXVIII.—NUMBERS OF BACTERIA AND AMMONIA PRODUCTION IN
PARTIALLY STERILISED SOILS.

| Soil Treatment. | Numbers of Organisms per grm. of Dry Soil, in Millions, Gelatin Plate Cultures. | | | | | Protozoa Found. | Ammonia and Nitrate Produced after 68 Days |
|-----------------|--|------------------|-------------------|-------------------|--------------------|--------------------|---|
| | At Beginning. | After 7 Days. | After 21 Days. | After 68 Days. | After 142 Days. | | |
| Untreated | 11 | 10 | 12 | 11 | 4 | C.A.M. | 14 |
| Heated to 40° | 7 | 9 | 10 | 8 | 3 | C.A.M. | 15 |
| " " 56° | 2 | 14 | 16 | 38 | 48 | M. | 60 |
| " " 70° | 2 | 17 | 11 | 24 | 27 | M. | 38 |
| " " 100° | 0.01 | 17 | 22 | 10 | 10 | — | 44 |

C = ciliates. A = amœbæ. M = monads.

Further, intermediate effects are obtained when a series of organic liquids of varying degrees of toxicity is used in quantities gradually increasing from small ineffective up to completely effective doses. The detrimental factor is not completely suppressed but sets up again after a time, so that the rise in bacterial numbers is not sustained. But the parallelism with ciliates and amœbæ is still preserved: they are completely killed when the detrimental factor is completely put out of action; they are not completely killed, but only suppressed to a greater or less degree, when the detrimental factor is only partly put out of action.

Now this parallelism between the properties of the detrimental factor and the protozoa is not proof that the protozoa constitute the limiting factor, but it affords sufficient presumptive evidence to justify further examination.

Soil Protozoa.

The preceding experiments show that protozoa commonly occur in soils but they give no information as to the kinds, the probable numbers, or the state in which the protozoa exist, whether active or simply as cysts.

A protozoological survey of the soil has been begun, and in order to give it as permanent a value as possible the investigations are not confined to the narrow issue whether soil protozoa do or do not interfere with soil bacteria, but they are put on the broader and safer lines of ascertaining whether a trophic protozoan fauna normally occurs in soil, and if so, how the protozoa live, and what is their relation to other soil inhabitants.

The first experiments by Goodey dealt mainly with ciliates (110a) and indicated that these protozoa were present only as cysts. Subsequent investigations, however, by Martin and Lewin (191) established the following conclusions:—

1. A protozoan fauna in a trophic state normally occurs in soils.
2. The trophic fauna found in the soil differs from that developing when soil is inoculated into hay infusions,¹ and *vice versa* the forms predominating in the hay infusions do not necessarily figure largely in the soil.
3. The trophic fauna is most readily demonstrated, and is therefore presumably most numerous, in moist soils well supplied with organic manures, *e.g.* dunged soils, sewage soils and especially glass-house "sick" soils.

The enumeration of the protozoa in the soil is carried out by means of a dilution method somewhat similar to that adopted for soil bacteria. It is already clear that amœbæ and flagellates are present in at least thousands per grm. of soil, while ciliates can be found only in hundreds. Some of the organisms appear to be new to science, and many of them are of considerable interest.

The presence of protozoa is not peculiar to British soils: they have been found in Egypt,² France,³ Italy,⁴ Germany,⁵ the United States, and elsewhere. Methods have been devised

¹ This is not necessarily true of all artificial media.

² Ronald Ross and D. Thomson, *Egyptian Sand Amœbæ* (*Proc. Soc. Med. Sect. Epidem.*, 1916, **9**, 33), and H. Sandon (Rothamsted).

³ In the Rothamsted laboratory.

⁴ A. Cauda and C. Sangiorgi (Turin), *Cent. Bakt. Par.*, 2 Abt., 1914, **42**, 393.

⁵ R. Oehler, *Arch. f. Protistenkunde*, 1916, **37**, 175; 1919, **40**, 16.

by D. W. Cutler and Miss L. M. Crump at Rothamsted, by Waksman at the Rutgers College (1926), by Kopeloff, Lint and Coleman at the New Jersey Experiment Station (1952), and by others, for estimating their numbers and activities.¹

There has been much discussion as to whether protozoa are normally active in the soil or whether they are simply there as cysts. Waksman (1926) recognises a trophic fauna. Sherman (1921), Koch,² Moore,³ Fellers and Allison,⁴ consider the protozoa are not active because they cannot be seen when soil is examined under a microscope.

D. W. Cutler (1930) has, however, found a satisfactory explanation of the difficulty of seeing living protozoa in the soil. He finds that the organisms rigidly adhere to the soil particles and indeed up to a certain limit they can be completely removed from a suspension by shaking for a few minutes with soil. The saturation capacity of the soil is high; at Rothamsted it is 1,500,000 or 2,000,000 per gram., a figure considerably in excess of the numbers present, and only in exceptional cases can organisms be dislodged sufficiently readily to be recognised under the microscope.

At Rothamsted frequent estimations are made of the number of protozoa found in certain arable soils. The method (1930) discriminates between cysts and active forms, and 9 species of flagellates, 5 of amœbæ, 2 of thecamœbæ, and 3 of ciliates are enumerated. Table LXXIX. shows the order of values frequently obtained. It is difficult to explain these high values if they simply represented cysts blown in from ponds.

The numbers are considerably higher in autumn and spring than in summer, and they are higher in summer than in winter, and they are much higher on the plot receiving dung than on that continuously unmanured.

¹ See N. Kopeloff and D. A. Coleman for a review of the investigations up to 1917 (*Soil Sci.*, 1917, 3, 197-269).

² G. P. Koch, *Journ. Agric. Research*, 1915, 4, 511; *Soil Sci.*, 1916, 2, 163.

³ G. T. Moore, *Science*, N.S., Nov. 8th, 1912; see also E. J. Russell, *Science*, N.S., April 4th, 1913.

⁴ C. R. Fellers and F. E. Allison, *Soil Sci.*, 1920, 9, 1.

TABLE LXXIX.—NUMBERS OF PROTOZOA AND OF BACTERIA PER GRM. OF SOIL FREQUENTLY FOUND ON TWO BROADBALK PLOTS. CUTLER AND CRUMP.

| | Broadbalk Dunged Plot. | | Broadbalk Continuously Unmanured. | | Active Forms. | Approximate Diameter. |
|---------------|------------------------|---------------|-----------------------------------|---------------|---|-----------------------|
| | Winter Total. | Summer Total. | Winter Total. | Summer Total. | | |
| Flagellates . | 150,000 | 600,000 | 5,500 | 15,000 | 15 to 95 per cent. of total in all cases. | 7.5-15 μ |
| Amœbæ . | 5,000 | 15,000 | 40 | 2,000 | | 8-22 μ |
| Thecamœbæ . | — | 1,000 | — | — | | 15 μ |
| Ciliates . | 50 | 200 | — | — | | 20-40 μ |
| Bacteria . | 10,000,000 | 24,000,000 | 4,000,000 | 5,000,000 | | 1-4 μ |

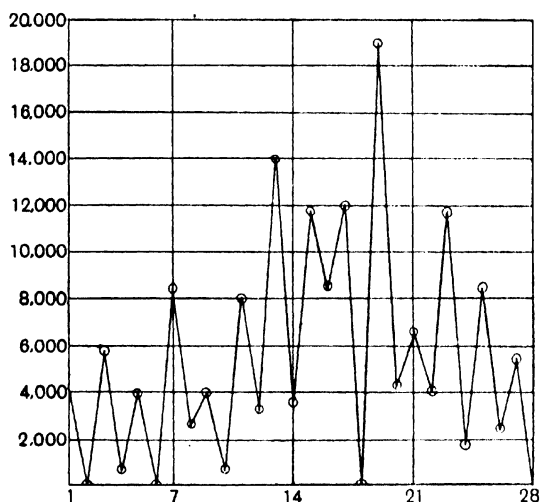


FIG. 28.—Daily counts of active flagellates (three species) in Broadbalk Plot 2 (dunged) (Cutler and Crump, 73c). The numbers are in thousands per gm., and show a remarkable periodicity.

The investigations have further shown that the numbers, while fairly regular on a uniform plot of land at a given time, do not remain constant, but vary from day to day. The proportion of active forms varies considerably, but on 50 per cent. of the days it exceeds 90 per cent. of the total number. The daily variations of three species of active flagellates on the Broadbalk dunged plot are shown in Fig. 28, and those of the

amœbæ in Fig. 29. These variations are not accidental and their cause is being investigated.

The rapid daily fluctuations in numbers apparently bear no relationship to external conditions, such as moisture and temperature. In order to obtain further information daily counts are being made at Rothamsted of the protozoa and bacteria in a field soil for a period of 365 consecutive days.

Numbers of Bacteria & Protozoa, Broadbalk.

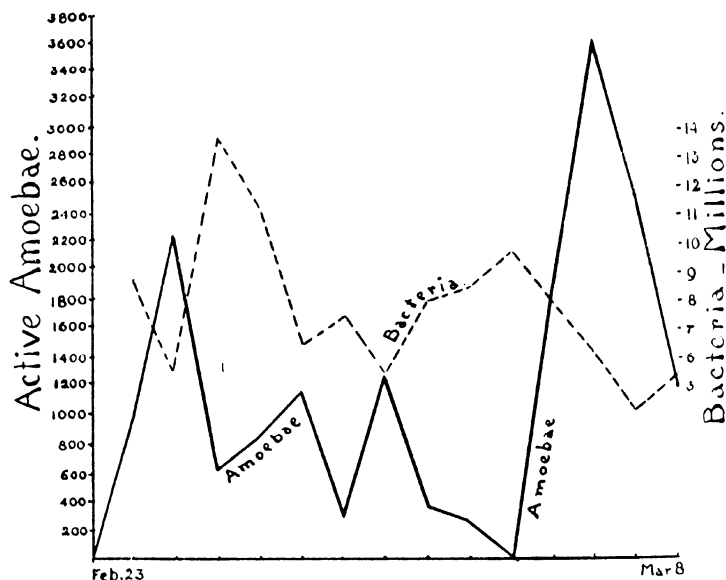


FIG. 29.—Daily counts of active amœbæ and of bacteria in Broadbalk Plot 2 (dunged) (Cutler and Crump, 73c). The active amœbæ are given in thousands, and the bacteria in millions, per grm. of soil.

These observations when completed will also give important information as to the relationship between numbers of bacteria and protozoa. The result of fourteen consecutive daily counts made in February, 1920, is shown in Fig. 29: these show that the numbers of active amœbæ and of bac-

teria are in inverse relationship—when one is high the other is low.¹

This relationship appears always to hold when counts are taken at short intervals. Since amœbæ normally feed on bacteria and do not live saprophytically they seem indicated as suppressors of bacterial numbers; they are, however, probably selective in their food, and it is possible that all soil bacteria are not equally affected by them.

The effect of flagellates in the soil is quite unknown. They do not necessarily feed solely on bacteria, but can and frequently do utilise other substances, including amino-acids.² Thus it would appear that they must effect some changes in the soil. Their large numbers and rapid fluctuations suggest an important part in soil economy which at present is unknown.

If protozoa are detrimental to soil bacteria it ought to be possible to reduce bacterial numbers in protozoa-free soil by the introduction of a protozoan fauna. Considerable importance is attached by Sherman and others to the fact that this fundamental experiment has not yet been satisfactorily carried out, or at any rate not more than once or twice, only A. Cunningham³ and T. Goody (110*b*) having reported decreases in numbers.

The experiment is admittedly crucial, but it is very difficult and is not likely to succeed until more is known of the life histories and physiology of the particular organisms concerned, and of the conditions necessary for their growth in soil. Cutler's results (Fig. 29) are difficult to explain in any other way except by supposing that active amœbæ are detrimental to bacterial numbers.

The present position in the controversy that has arisen may

¹ The relationship thus resembles that obtaining in water: see Otto Hunte-müller, *Vernichtung der Bakterien in Wasser durch Protozoen* (*Arch. f. Hyg.*, 1905, liv., 89-100); Fehrs, *Die Beeinflussung der Lebensdauer von Krankheitskeimen in Wasser durch Protozoen* (*Hyg. Rundschau*, 1906, xvi.); P. Th. Müller, *Ueber die Rolle der Protozoen bei der Selbst-reinigung stehenden Wassers* (*Arch. f. Hyg.*, 1912, 75).

² See H. G. Thornton and Geoffrey Smith, *On Certain Soil Flagellates* (*Proc. Roy. Soc.*, 1914, 88 B, 151-165).

³ *Journ. Agric. Sci.*, 1915, 7, 49-74.

be briefly summed up. Most workers now recognise protozoa as a normal component of the soil population. Many admit the existence of a trophic protozoan fauna. Some, *e.g.* Waksman (1926), recognise that certain of the trophic fauna act detrimentally on soil bacteria, but few are prepared to admit that they act detrimentally on the decomposition processes, such as ammonification, nitrification, etc. In the writer's opinion the evidence is in favour of the existence of the trophic protozoan population acting detrimentally on soil bacteria, but as yet there is no direct evidence to show whether, or to what extent, the decomposition processes in the soil are affected.

The Effect of the Complexity of the Soil Population on Productiveness.

Apart from the effect of partial sterilisation there is other evidence that simplification of the soil population may lead to increased productiveness, and conversely that a more complex population may be relatively less effective as producers of plant nutrients. It has been observed by practical men in various countries that certain soil conditions harmful to the growth of organisms were ultimately beneficial to productiveness; such are long continued and severe frosts, long drought (especially if associated with hot weather),¹ sufficient heat, treatment with appropriate dressings of lime, gas lime, carbon disulphide, etc.

Further, it has been observed that conditions which are undoubtedly favourable to life, such as the combination of warmth, moisture, and organic manures found in glass-houses, lead to reduced productiveness after a time. This phenomenon is spoken of as "sickness"² by the practical man.

¹ For references see E. J. Russell, *Journ. Roy. Ag. Soc.*, 1910, 71, 9; also J. A. Prescott (228).

² "Sickness" is a very vague term and no doubt includes many dissimilar cases. Other instances of "sickness," which may refer to something quite different, are recorded by Hudig (*Landw. Jahrb.*, 1911, 40, 613-644) and Loew (*Porto Rico Report*, 1910). Some soil in Orkney was said to be "oat-sick" but experiment revealed nothing (*Aberdeen Leaflet* 15, 1911).

It is difficult to account for this result on the old view that the useful plant-food making bacteria are the only active micro-organisms in the soil. On the other hand, the view that detrimental organisms are also present readily explains the observed facts.

The "sickness" that affects the soils of glass-houses run at a high pitch (such as cucumber-houses) and less slowly those run at a lower pitch (such as tomato-houses) has been investigated in some detail owing to its great technical importance (Russell and Petherbridge, 241*e*). It was traced to two causes: an accumulation of various pests, and an abnormal development, especially in cucumber-houses, of the factor detrimental to bacteria. The properties of this factor show that it is identical in character with that present in normal soil, and strongly indicate its biological nature. No evidence of a soluble toxin could be obtained but the possibility of insoluble toxins was not excluded. On the other hand, some remarkably interesting protozoa and allied organisms have been picked out from these sick soils and described by Martin and Lewin (191) and T. Goodey. Finally it has been shown that the whole trouble can be cured by partial sterilisation, and methods suitable for large scale work have been investigated and are now in use in practice. Steam heat at present proves most convenient, but the suitability and detailed effects of lime have been studied by Hutchinson and McLennan (140*c*) and of various antiseptics by Buddin (61), Russell, and others.¹

Again, it should be stated that the views set out here are not generally accepted by American workers (see J. M. Sherman, 261). Bolley attributes the whole trouble in North Dakota to plant diseases,² which, of course, may be the predominating factor there. It is possible that there are important differences in soil population in British and American

¹ See *Journ. Roy. Hort. Soc.*, 1920, 45, and Reports of the Nursery and Market Garden Expt. Station, Cheshunt, Herts, 1917, onwards.

² H. L. Bolley, *North Dakota Bull.*, 107, 1913; *Science*, 1910, 32, 529-541, and 1913, 38, 249-259.

soils, but it is highly probable that much of the apparent discrepancy will disappear with further investigation.

The Action of the Plant on the Micro-organic Population of the Soil.

The whole existence of the soil population is intimately bound up with the growing plant: from this source it obtains its supplies of energy and of those nitrogen compounds the changes in which form the chief theme of soil bacteriology. These effects are mainly exercised by the residues of dead vegetation; there are, however, others hardly less potent produced by the living plant.

A growing plant removes a considerable amount of soluble material from the soil,¹ and thus modifies the composition of the soil solution which serves as part of the medium in which the organisms live. Further, the plant roots are continually giving off carbonic acid. It might be supposed that this would cause the surrounding medium to become acid, but as a matter of fact the contrary happens and the medium becomes alkaline. This has been known for some time in the case of water cultures; the explanation offered is that the plant takes up the acid radicle of the sodium nitrate and leaves behind the base, which immediately appears as the carbonate. Hall and Miller (120*b*), and subsequently Maschhaupt (192) have obtained evidence of a similar action in the soil, the calcium nitrate formed during nitrification being converted into calcium carbonate while the nitrate radicle is taken by the plant. These effects, involving as they do an accumulation of calcium compounds in the surface soil, are favourable to micro-organisms; others are unfavourable, such as the removal of moisture by the plant and the evolution of carbon dioxide from the roots. Some investigators have supposed that the plant secretes part of the mineral matter which it has taken up but no longer needs, and if so this would affect the micro-organisms.

Burd, in California (62*b*), recognises three periods in the

For amounts see Appendix II., p. 357.

growth of barley: up to the time of formation of the head the rate of absorption progressively increases till finally the amounts of nitrogen and potassium in the plant reach a maximum. During the period of translocation of material into the developing heads, however, there is not only a decreased rate of absorption from the soil but a substantial loss of nitrogen and potassium from the aerial parts of the plant. Towards the end of this period some of the lost materials are regained. In the third period ripening is completed, absorption ceases and losses are resumed. These losses are experimentally traced from the aerial parts alone, and it is impossible to assert that they take place from the whole plant owing to the difficulty of completely extracting the roots from the soil. The presumption is, however, that such losses do take place.¹

It is interesting, and may be significant, that Russell and Appleyard (241*g*) observed a marked increase in CO₂ content of the atmosphere of cropped soils during the period of ripening, when these losses from the plant are presumably taking place.

We have now to ascertain how these various effects react on the soil micro-organisms. Several attempts have been made to correlate bacterial numbers with the nature of the crop, but the data hitherto obtained are inadequate for satisfactory discussion. There is, however, considerable evidence to show that nitrate accumulates more readily on uncropped than on cropped soils, even after allowance is made for the quantity absorbed by the plant. Table LXXX. gives some of the results obtained at Rothamsted.

To some extent climatic factors come into play, the cropped land frequently being somewhat cooler and drier than the fallow. But this does not hold universally, and the phenomenon has been observed under such widely different conditions that

¹ Le Clerc, *U.S. Dept. of Agric. Year Book*, 1908, 389-402; also André, *Compt. Rend.*, 1910, 151, 1378-82, support the view that the losses occur by washing from the leaf rather than from the root. For mass of data suggesting root losses see Wilfarth, Römer, and Wimmer, 309*b*.

TABLE LXXX.—NITRATES IN CROPPED AND UNCROPPED SOILS AT ROTHAM.
STED EXPRESSED AS N., LB. PER ACRE. RUSSELL (241f).

| | June, 1911. | | July, 1912. | |
|--|--------------|---------------|--------------|---------------|
| | Fallow Land. | Cropped Land. | Fallow Land. | Cropped Land. |
| N. as nitrate in top 18 in. of soil (June) | 54 | 15 | 46 | 13 |
| Nitrogen in crop, lb. per acre | — | 23 | — | 6 |
| Total lb. per acre | 54 | 38 | 46 | 19 |
| Deficit in cropped land, lb. per acre | — | 16 | — | 27 |
| Expressed as N., parts per million. | | | | |
| N. as nitrate 0 to 9 in. depth | 12 | 4 | 8 | 2 |
| 9 to 18 in. depth | 9 | 2 | 10 | 3 |

climatic factors seem to be ruled out. In 1905 Warington showed that the amount of nitrate in the drainage waters from Broadbalk field was considerably less than was expected from the manure supplied and the crop reaped. He thought that denitrification might account for some of the discrepancy but not for all, as it could hardly be supposed to act in dry summer weather; he further suggested that the nitrate might be taken up by the plant and then somehow lost before harvest. More recently Lyon and Bizzell (183) found more nitrate on land cropped with maize (after allowing for the nitrogen present in the crop) than on fallow land of similar history, and concluded that the growing maize plant in some way stimulated nitrification. During the latter part of the life of the plant less nitrate was found in the cropped than in the fallow land, and the further conclusion is drawn that nitrification is inhibited by the conditions accompanying the decreasing activities of the roots. On the other hand, where oats and potatoes were grown the nitrates were never so high in the cropped as in the uncropped land, again, apparently, after allowing for what has been absorbed by the crop. The following amounts of nitrogen as nitrate occurred in parts per million of soils are given in Table LXXXI. :—

TABLE LXXXI.—NITROGEN AS NITRATE IN CROPPED AND UNCROPPED SOILS, ITHACA, N.Y. (LYON AND BIZZELL). PARTS PER MILLION.

| 1908. | Fallow Land. | Land Carrying Maize. | 1909. | Fallow Land. | Land Carrying Oats. |
|-----------|--------------|----------------------|------------|--------------|---------------------|
| May 19 . | 4'9 | 3'9 | April 22 . | 19'0 | 10'9 |
| June 22 . | 10'9 | 9'3 | June 24 . | 12'6 | 2'5 |
| July 6 . | 14'5 | 14'2 | July 12 . | 12'5 | 1'0 |
| July 27 . | 42'1 | 43'2 | August 7 . | 18'4 | 0'8 |
| August 10 | 40'3 | 37'3 | — | — | — |

It is interesting to observe that the figures are generally of the same order as at Rothamsted excepting only in July and August, 1908. We have never observed, however, any increase in nitrate on cropped land such as is recorded in their maize experiments; our results with wheat and barley have always shown a decrease, like theirs with oats. Leather's experiments in India (167*b*) and Prescott's in Egypt (228) also show a decrease. The nitrate in the drainage water from the fallow gauges at Pusa contained respectively 261.5 and 209.6 lb. per acre during the period 1907-9, while that in the drainage water and crops of the gauges cropped with grass accounted only for 128.4 and 115.6 lb. per acre over the same period. The final rainfall before the account was made up was so heavy as to deplete the gauges of nitrate, so that no error arises through the retention of nitrate in the soil.

Deherain's experiments made at Grignon, near Paris (81*b*), between 1892 and 1897, also showed much more nitrate coming from the fallow lysimeters than from those covered with crops, even after allowing for what was absorbed by the crop. In this case, however, it is uncertain how much nitrate was left in the soil, the rainfall probably being insufficient to wash it all out.

Thus it seems to be an established fact that less nitrate usually accumulates in cropped land than in fallow land, even after allowing for what is absorbed by the crop. The wide range of climatic conditions under which the result is obtained seems to preclude any assumption that it is due to the effect

of the crop on the temperature or moisture content of the soil.

Two hypotheses are possible: there may be a diminished production of nitrate in cropped land, indicating an adverse effect of the growing crop on bacterial activity, or there may be some process destructive of nitrates (possibly by conversion into protein)¹ at work in the cropped soil that does not go on in fallow soil.

Destruction of nitrates is at least as probable as a diminished bacterial activity. It may quite well happen that portions of the roots and rootlets are decomposed during the life of the plant, and if their nitrogen content is insufficient, the organisms might assimilate some of the soil nitrates (p. 210). This view is consistent with certain observations which are otherwise difficult to explain, and which seem to indicate an increased rather than diminished bacterial activity in the neighbourhood of the growing plant. Working with the irrigated soils of Utah, McBeth, and Smith (185*a*) found that the "nitrifying power" (*i.e.* the power to produce nitrate when incubated under optimum conditions with dilute ammonium sulphate solution) was higher on cropped than on fallow land. Again, Le Clerc found higher bacterial numbers under cow-peas than in the fallow plots.² A similar result was obtained in Joshi's pot experiments with other crops.³

On the other hand, the alternative view that plant growth depresses bacterial activity seems to be supported by Harrison and Aiyer's investigations in paddy soils already quoted (p. 213). The production of methane and hydrogen was markedly less on the cropped than on the fallow land. There is no question here of deficient water supply or temperature, and the conclusion of the authors is that the crop reduced bacterial action either by giving out some bacteriotoxin or by absorbing some of the products of the early stages of decomposition.

¹ Burd (62*a*, p. 304) suggests that this change occurs in Californian soils.

² *Journ. Ag. Res.*, 1916, 5, 439-447.

³ *Memoirs Dept. of India, Bact. Ser.*, 1920, 1, 247-276.

CHAPTER VIII.

THE SOIL IN RELATION TO PLANT GROWTH.

WE are now in a position to summarise the effect of the various soil conditions on the growth of plants. The soil serves several functions; it affords a more or less continuous supply of food and water, it regulates the temperature and provides anchorage for the roots without interfering too much with the air supply. The extent to which any of these things is done depends on the nature of the particles and, therefore, varies from soil to soil. As the requirements of plants also vary in degree, the different soil types have come to possess their own flora made up of those plants that tolerate the conditions better than other possible competitors, and on cultivation they show different agricultural characteristics. And since the natural flora is profoundly affected by competition, a small factor operating for a sufficient length of time may produce extraordinary differences in vegetation, as is well seen on the Rothamsted grass plots.

At the same time the plant is not rigidly unalterable but possesses considerable power of adaptation to its surroundings: in rooting depth, size of leaves, glaucous characters, etc.

In discussing the relationship between plant growth and the soil it is necessary to take into account not only the *intrinsic* properties of the soil due to the nature of its constituent parts, but the *extrinsic* properties impressed by topographical and climatic factors. A certain indefiniteness thus becomes unavoidable, because none of the latter can be expressed in exact measurements. This point is well illustrated by the water supply. The amount of water in the soil at

any time is the balance of gains over losses. The gains depend on the rainfall (*i.e.* climate), and on the amounts of water derived by drainage from higher land (*i.e.* topographical position), or by surface tension from the subsoil; the losses depend on the extent to which the subsoil facilitates drainage and on the rate of evaporation, which in turn depends on the temperature, the exposure of the soil, the velocity of the wind and the mode of cultivation. Five factors have, therefore, to be considered: (1) the nature of the soil particles, (2) the amount and distribution of the rainfall, (3) the position of the soil in relation to the land round about it, its aspect, shade, and any other factors affecting its relative temperature and water supply, (4) the depth of the soil, (5) the nature of the subsoil, especially its perviousness to air, water, and plant roots. Any of these factors may, within certain limits, dominate the rest and profoundly affect the flora and the agricultural value; thus a sandy soil may, without any change in type, be a dry and barren heath if underlain near the surface with rock or gravel, a highly fertile fruit or market-garden soil if sufficiently deep, or a stagnant marsh giving rise to peat if so situated that water accumulates and cannot drain away.

No sharp division can be drawn between the intrinsic and extrinsic properties. The significant units in the soil that determine its intrinsic properties are the compound particles made up of the ultimate mineral particles—clay, silt, sand, etc.—together with calcium carbonate and organic matter derived from plant remains. Now the nature and amount of the organic matter are greatly influenced by the extrinsic conditions—the temperature and water supply—that have obtained in the past. Moisture, warmth, and aeration favour the development of a succulent vegetation which sheds easily decomposable leaves and stems on to the soil; earth-worms and bacteria can now flourish and produce the normal decomposition products that go to make up “mild humus” and a fertile soil. Dryness necessitates a narrow-leaved xerophytic vegetation, the leathery fragments of which mingle with the soil, but afford a very indifferent medium for the growth of

earth-worms and bacteria, so that little decomposition goes on, and a barren sand results. Wetness and lack of aeration necessitate special vegetation and decomposition agents, and there may result a "mild humus" if sufficient calcium carbonate is present to determine a calcicolous flora, or an "acid humus" in the contrary event. Even such small differences as affect the liability to late frosts may affect the native vegetation and therefore the humus: for example, bracken is more readily killed than heather and is therefore less likely to survive at levels where late frosts are common.

Thus the soil is very much the result of circumstances; its character is determined in part by the rock from which it was derived, and in part by subsequent events, particularly the temperature and water supply it happened to obtain, in other words, its climate. A given set of mineral particles may, under different climatic conditions, give rise to soils wholly different in agricultural value and in natural flora. This thesis was first set up by Hilgard, but it has been greatly developed by the Russian investigators and, indeed, has been one of their most striking contributions to the study of the soil (85, 266).

Further, the farmer has discovered how to build up these compound particles by cultivation and thus change to a very great extent the relation of the soil to the plant: the process consists in adding dung, or ploughing in green crops, adding lime, exposure to frost, and skilful (but wholly empirical) cultivation, and, although not very rapid, it takes only a few seasons to accomplish.

But while the ultimate mineral particles do not entirely control the relationships of the soil to vegetation they fix the limits within which these relationships may vary and beyond which they cannot pass. Farmers recognise five great divisions: clays, loams, sands, calcareous soils and soils rich in organic matter, all shading off into one another and without sharp lines of demarcation, but representing classes of soil that cannot be changed one into the other by any cultivator's artifice.

Calcareous Soils.—The simplest case is presented by soils

where the calcium carbonate exceeds about 10 per cent. and dominates every other constituent, becoming the controlling factor in determining the soil properties. The conditions here seem to be extraordinarily well suited to plant and animal life. Bacteria are numerous and active, rapidly oxidising organic matter. Hosts of animals, wireworms, earthworms, and others live in the grass land, and even get into the arable land, honeycombing the soil with their passages, puffing it up or "lightening" it considerably, and encouraging the multiplication of moles. Rabbits abound in dry places. Vegetation is restricted on thin exposed soils, but becomes astonishingly varied where there is sufficient depth of soil and shelter to maintain an adequate water supply. Ash is the characteristic tree in the north and west, and beech in the south of England, and there is a great profusion of shrubs—buck thorn, spindle, guelder rose, dogwood, hawthorn, hazel, maple; and especially of flowering plants—scabious (*S. Columbaria*), the bedstraws, vetches, ragwort, yellow wort (*Chlora perfoliata*), salad burnet (*Poterium sanguisorba*), lady's fingers (*Anthyllis*), *Linum catharticum*, *Bromus erectus*. Still more remarkable, perhaps, is the fact that a few plants—the so-called calcifuges—do not occur. Where the amount of calcium carbonate is too high plants tend to become chlorotic; Chaazit showed that vines suffered badly when 35 per cent. or more was present, but not when the amounts fell to 3 per cent.¹ Mazé (197) attributes part of the action to the rendering insoluble of zinc, manganese, etc., necessary for complete growth (p. 56).

Investigations in Porto Rico (105), where a considerable portion of the arable land is sufficiently calcareous to produce nutritional disturbances in crops, show that bush beans (*Phaseolus nanus*) and radishes are unaffected by even 35 per cent. of CaCO_3 ; sunflowers, soy beans, and sugar canes are somewhat depressed; while sweet cassava (*Manihot palmata*), rice and pine-apples were considerably depressed by this amount. The

¹ See *Revue de Viticulture*, 1902, xviii., 15, and also Molz, *Centr. Bakt. Par.*, Abt. ii., 1907, xix., 475.

amount of nitrogen, potash, and phosphoric acid in the various crops was apparently unaffected by the carbonate, but the iron was notably depressed.

The reason for these special features is not clear, but is probably not to be found in any one factor. The plants do not require such high amounts of calcium carbonate, because they will wander on to an adjacent loam ; even the absence of the calcifuges cannot always be attributed to a supposed toxic effect of calcium carbonate, because in other regions, or in pot experiments, some at any rate of them may be found growing in its presence. The lupin affords an example. It is much grown in Germany and is supposed to suffer in presence of chalk (Kalkempfindlichkeit) : Hiltner proposed to use ferrous sulphate to counteract this trouble. But in experimental plots Pfeiffer and Blanck¹ obtained even better growth in presence of chalk than in its absence ; possibly the beneficial effect was on the nodule organism rather than on the plant. Rhododendrons and azaleas in this country are said to be intolerant even of traces of chalk, for which reason hard water is not used for them ; this case deserves further investigation. In a prolonged investigation near Karlstadt Kraus (155) found no plant occurring exclusively on soils with even approximately equal content of calcium carbonate, although some preferred more, *e.g.* *Festuca glauca*, *Teucrium montanum*, and *Melica ciliata*, while others preferred less, *e.g.* *Brachypodium pinnatum*, *Koeleria cristata*, and *Hieracium pilosella*. True chalk plants were found on the adjoining sand, especially when some calcium carbonate was present, although the true sand plants did not wander on to the chalk. In such cases of displacement or "heterotopy" it was shown that the general physical conditions of the two locations were similar in spite of their wide difference in chemical composition. Kraus, therefore, argues that the true chalk plants inhabit chalk soils not because they need much calcium carbonate, but because they find there the general physical and chemical conditions they require. Dr. Salisbury's view (242)

¹ *Mitt. Land, Inst., Breslau, 1914, 7.*

is that two conditions come in: wetness and acidity—from both of which chalk soils are free; the so-called calcicolous plants will, however, grow elsewhere if these conditions are absent; thus he finds beech on non-calcareous soils on the continent so long as these soils are dry. Dr. Brenchley finds that the calcifuges of the West of England are not all calcifuges in the Eastern counties, while Massart¹ showed that the typical calcifuge, *Calluna vulgaris*, grows on the “lime-stone pavements” of the West of Ireland.

The fact that a calcareous rock lies beneath is no proof that the soil itself is calcareous: on the contrary, the soil may often contain practically no calcium carbonate, either because it has become decalcified by rain, or because it really represents some deposit of wholly extraneous origin.

The agricultural value of chalk soils depends very largely on their depth, and is much greater in valleys where the soil and water collect than on the higher ground where the soil is thinner. The two defects most in need of remedy are the lack of organic matter and the tendency to become light: these are met by additions of dung or other organic manures, by rolling and cultivating with heavy instruments, and above all by feeding animals on the land with the crops actually growing there and with purchased food, a process known as “folding”. Heavy wooden ploughs are still in use, and until recently were worked in many places by large teams of heavy oxen. Sheep are by far the most suitable animals to be fed on the land, and they form the centre round which the husbandry of chalk districts has developed; indeed, so important are they that each chalk region has evolved its own breed of sheep—South Downs, Hampshires, etc. As fertilisers potassic manures, especially kainit, are generally profitable; superphosphate is needed for turnips, and in wet districts basic slag is useful on the grass land. Skilful cultivation is always necessary, or the soil dries into hard, steely lumps that will not

¹ *Brit. Assoc. Report*, 1911, 564. The case of *Calluna* is discussed by M. C. Rayner in *Annals of Botany*, 1915, 29, 97-133, and *Sphagnum* by M. Skene, *ibid.*, 1915, 29, 65-87.

break down. And, lastly, the pre-eminent suitability of the chalk to plant and animal life has its disadvantages; no soils are more prone to carry weeds, turnip "fly," or wireworm. Skilful management is the keynote of success and it generally obtains, the bad farmers not usually surviving many seasons.

Black Soils or Humus Soils.—In these the organic matter dominates all other factors, but the case is more complex than the preceding, because several varieties of organic matter occur, giving rise to several types of soil.

There is a sharp distinction between:—

1. True peat, such as is found in moorlands, acid in nature, and commonly occurring in wet districts and regions of high rainfall or low temperature. This again is subdivided into high moor and low moor. The organic matter shows definite structure.

2. Fen, neutral in nature, occurring more locally: in England mainly in the Eastern counties. The organic matter usually shows no structure.

Fen land when drained has a high agricultural value, being worth some £2 per acre annual rent and producing considerable crops of potatoes, celery, and wheat.

True peat, on the other hand, has little agricultural value in its natural state and where high-lying is largely waste land, being unsuited to the growth of many plants and micro-organisms¹ (p. 269). In this country it may have a certain sporting value, but elsewhere it lacks even this.

Peat Soils.—A number of schemes have been projected for utilising the great peat areas, and they may roughly be grouped into two classes:—

1. Ameliorating substances (such as lime, artificial manures, etc.) are added, and the peat is cultivated as if it were normal soil. This is possible only when the deposits do not lie too high.

¹ For studies of nitrification and other bacterial actions in moorland soils see E. Gully, *Das Nitrifizierungs- und Nitritbildungsvermögen der Moorloden* (*Landw. Jahrb. Bayern*, 1916, 6, 1-81); Th. Arnd (6), *Zur Kenntnis der Nitrifikation in Moorböden* (*Centr. Bakt. Par.*, 11., 1919, 49, 1-51).

2. The peat is removed and sold, and if the climate allows the underlying formation is:—

- (a) Ploughed up, if it is clay or sand.
- (b) Covered with town refuse and then cultivated, as at Chat Moss.
- (c) Warped, *i.e.* systematically flooded with tidal water carrying silt till several feet of soil have been formed; this is only possible in a few areas, *e.g.* in Lincolnshire, lying below high water-level.

The first of these methods is in use in Ireland¹ and on the continent; it is much investigated at the experiment stations at Jonköping (Sweden) by H. von Feilitzen, at Bremen (Prussia), Munich, and Arnheim (Holland). The second has been the subject of many experiments in England.

The removal and sale of peat is perfectly sound in principle. Peat is an asset of considerable value, but it is essentially a wasting asset; it disappears at a measurable rate after the drainage that is nowadays necessary. Under modern conditions peat cannot be conserved for future generations, and we are therefore fully justified in using it ourselves, even if the process be somewhat wasteful.

Peat may be made to serve three purposes:—

- (a) Fuel, after it has been cut and dried.
- (b) Litter, if it is sufficiently fibrous, or
- (c) It may be decomposed by heat, and made to yield valuable products, such as sulphate of ammonia, power gas, tar, etc.

Fen Soils.—The fen soils form an interesting group in the low-lying areas adjoining the river Ouse and its tributaries in Norfolk, Cambridge, etc. As already stated, the soil water is not acid but contains calcium carbonate: the vegetation is not of the acid-soil type and crops do not respond to lime. The main characteristics of these soils are their richness in lime and their very high content of nitrogen, of which no less than 3 per cent. is found in some cases (see p. 136).

The region was not much in cultivation till the great

¹ See Duncan for experiments in Ireland, *Journ. Dept. Agric., Ireland*, 1915.

reclamation schemes of the seventeenth century, when Vermuyden, the engineer, and the Duke of Bedford and other enterprising capitalists took the matter in hand and erected the great dykes, drains, and pumps that alone keep the land dry and usable. The water is thus artificially kept down and it can be maintained at any desirable level within the capacity of the pumps: the land is thus subirrigated, a feature which contributes no little to its extraordinary fertility.

Farmers distinguish two types of fen: the clay fen on the western side and the sandy fen on the eastern side of the region; the difference lies probably in the subjacent material, there being little evidence of any difference in the actual fen. The Kimeridge clay on the west lies about 5 feet below, but occasionally it comes above the surface and forms the rising ground on which alone dwellings could be built before the reclamation—the “*eyss*” or islands of the old days. On the east the fen is underlain by sand.

The most suitable crops are oats, wheat, and above all potatoes, the introduction of which some thirty years ago completely revolutionised fen husbandry. In smaller quantities mangolds, celery, mustard seed, cole seed, rye grass seed, buckwheat, and other seeds are grown. Corn crops, however, do not finish well: they start well but do not “*corn out*”. But where clay lies underneath a complete remedy lies in bringing up the clay and spreading it: this is done about once in twenty years. The soils shrink very much on drying, forming large cracks dangerous to animals and sometimes destructive to cart wheels. Oxidation is continually proceeding at a rapid rate and within living memory the fen has shrunk several feet: in many cases it only has another 5 or 6 feet to fall before disappearing altogether.

Fen soils do not require lime or nitrogenous manures, or, as a rule, potash. But they do respond in a marked degree to superphosphate, as shown by the following experiments made by the Cambridge Department of Agriculture:—¹

¹ *Cambridge Farmers' Bull.* No. 6. Two of the soils overlay clay, the third was over gravel.

| With Mangolds. | | | With Potatoes. | | |
|------------------------|-------|-------|------------------------|-------|-------|
| | Tons. | Cwts. | | Tons. | Cwts. |
| No manure | 11 | 2½ | No manure | 5 | 12 |
| 3 cwts. superphosphate | 16 | 2 | 4 cwts. superphosphate | 7 | 15 |
| 6 " " " | 21 | 13 | 8 " " " | 8 | 10 |

Bones also give good results, but basic slag appears to be without effect. Summer fallow has been observed to have a bad effect on fen soils.

In practice the clay fen soils after their periodical claying receive nothing but superphosphate: they are extraordinarily fertile, commonly yielding 8 tons of potatoes, 90 bushels of oats and 56 bushels of wheat per acre. The sandy fen soils are less fertile because they cannot be clayed except at great expense: the chief need again is for phosphate, but potash also is wanted.

The wonderful black earths of Russia, Canada, etc., are probably akin to the fen soils. The black soils of the Canadian prairies have been described by Shutt (265): under wheat cultivation they require no fertiliser; the similar Tchernozem of Russia and Hungary also carry practically nothing but wheat and receive little or no manure (85, 154*b*).

The "muck land" of the United States appears to be of the same type: it is underlain by shell deposits containing lime, and no structure can be detected in the organic matter: it differs from peat, however, in that it responds to lime and potassic fertilisers.

Clay Soils.—Clay soils are characterised by the presence of 20 to 50 per cent. of "clay" and similar quantities of silt and fine silt; in consequence of this excess of fine particles the size of the pores is so diminished that neither air nor water can move freely. Clay soils, therefore, readily become waterlogged and in time of drought may not sufficiently quickly supply the plant with water; in our climate, however, they are usually moist or wet. The high content of colloidal matter impresses marked colloidal properties: (1) the soil shrinks on

drying and forms large gaping cracks which may be several inches wide and more than a foot deep ; (2) it absorbs much water, a good deal still being held even when the soil appears to be dry ; (3) the water, however, moves only slowly, and it is not uncommon to find a fairly sharp line of demarcation between moist and dry soil, and for land to crack badly within a few feet of a ditch full of water ; (4) the soil readily absorbs certain soluble salts and organic substances. In addition the special clay properties are shown : plasticity and adhesiveness when wet, and a tendency to form very hard clods when dry. All these properties are much modified by calcium carbonate and intensified by alkalis ; the chalky boulder clay is usually fertile : on the other hand, liquid manure (which contains ammonium carbonate) and nitrate of soda (which gives rise to sodium carbonate in the soil) are both to be avoided.

Clay soils have had rather a chequered agricultural history. Originally covered with oak forest and hazel undergrowth they were early reclaimed for agriculture purposes by draining, applications of lime,¹ and, later, of ground bones. Wheat and beans were the great clay crops, and in the early part of the last century, under the combined influence of high prices, large drainage schemes and artificial stimulus to enclosure, great areas came into cultivation so that now only little unreclaimed clay remains, excepting where the forest was preserved for hunting. Crops grew well but ripened late ; a wet harvest was a terrible calamity. Bare fallowing was always necessary once in four years, and any of the intervening years might, if wet, be lost by the difficulty of getting on the land to sow the crop. When the price of wheat fell in the eighties many of these soils went out of cultivation and became covered with a mixed growth of grass and weed, which was grazed by stock and gradually deteriorated as the old drains choked up and the land became more and more waterlogged. *Aira cæspitosa*, "bent" grass (*Agrostis vulgaris*), yellow rattle (*Rhinanthus*

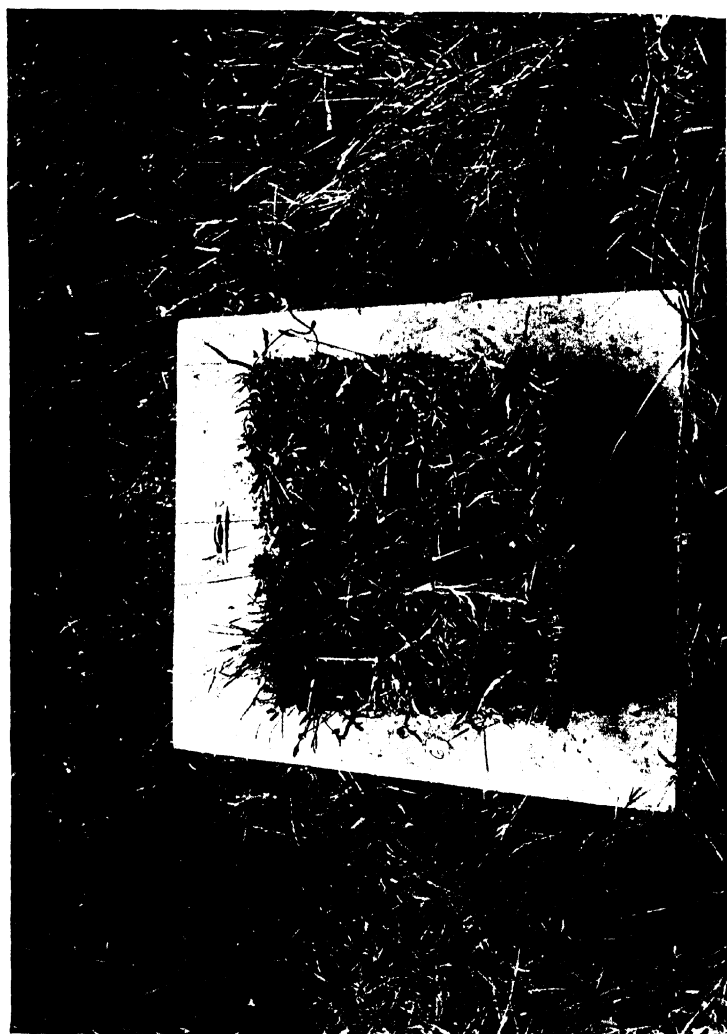
¹ E.g. see Gervase Markham, *Inrichment of the Weald of Kent*, 1683.

Crista-galli), and in drier places the quaking grass (*Briza media*) and ox-eyed daisy (*Chrysanthemum Leucanthemum*) are among the more obvious plants on these neglected fields; the only relics of the past are the field names and the high ridges or "lands" made years ago to facilitate drainage. But recently marked improvement has set in. Drainage is gradually being attended to, improved implements allow of better cultivation: mangolds, kohlrabi, and other fodder crops suitable for heavy soils have been grown, whilst additions of lime and phosphates (as basic slag) have markedly improved the herbage, favouring the development of white clover (*Trifolium repens*) and the pasture grasses, and crowding out the weeds. Fig. 30A and B shows specimens of herbage from some of Robertson's plots at Horndon-on-the-hill, Essex (London clay). Potassic fertilisers are not usually needed. Only in the dry eastern counties has the old arable cultivation survived.

It is commonly observed that plants growing on clay soils tend to have larger leaves, and to make shorter-jointed growth, than plants on sandy soils.

Many of the ecological and agricultural observations on clay need revising in view of the distinction which has recently been set up between the silty clays and the true clays. The former owe their heaviness to the presence of much fine silt which differs in colloidal properties from clay (p. 107), and is not flocculated by lime, frost, etc. Indeed, no way is known for ameliorating these soils and they are generally left as rather poor pasture. The true clays are often indistinguishable on casual inspection, but they behave differently on cultivation and respond to lime and good treatment whenever it is deemed worth while to improve them.

Sandy soils are formed of large silica particles deficient in colloidal matter, and therefore possessing little power of cohesion, or of retaining water or soluble salts. Hence they tend to be dry, loose, and poor in soluble substances--"hungry," the practical man calls them. Their behaviour towards vegetation depends very largely on their position, their depth, and the nature of the subsoil, these being the



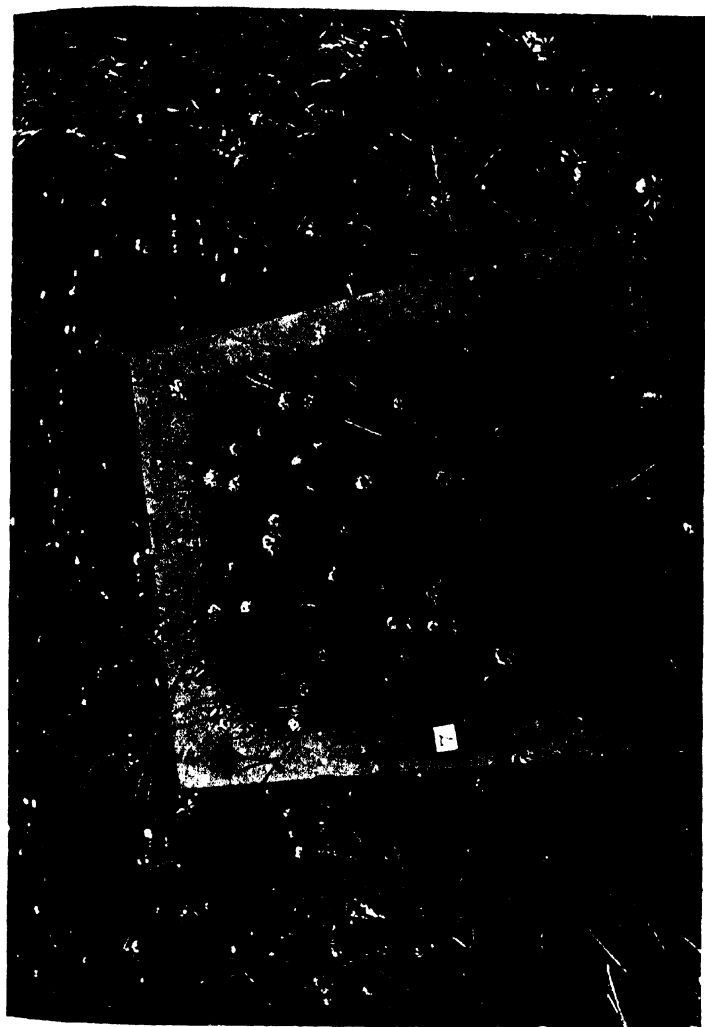


FIG. 308.—Adjoining plot, but treated with Gafsa phosphate, Feb. 27th, 1918. Photographed Aug., 1919.

factors that determine the water supply to the crop. The water supply is usually satisfactory when the surface soil contains sufficient clay and not too much coarse sand and gravel, and rests on a deep subsoil containing rather more of the finer particles. It is a further advantage if other land lies higher and furnishes a supply of underground water. In such cases the land is nearly always cultivated; it yields early crops of high quality rather than heavy crops, the tendency to drought inducing early maturation, while the absence of stickiness makes sowing an easy matter at any time. Fruit, nursery stocks, potatoes, and market-garden produce are often raised, and high quality barley is also grown. The winter feeding of sheep on the land is a common way of fertilising, but crops must be sown early, or the fertilising material is washed out unused, and the young roots have no time to strike into the subsoil before the surface layer dries out. High farming is the only profitable way of dealing with these soils; any carelessness in cultivation lets in hosts of weeds, such as poppies, knot-weed (*Polygonum aviculare*), spurrey (*Spergula arvensis*), sorrel, horsetail, convolvulus, creeping buttercup, and others. Crops should follow each other in rapid succession, any interval being a period of loss; under good management two or even three market-garden crops can be secured in the year, while in purely farming districts catch crops should always be taken. Organic manures are very necessary to increase the water-holding capacity; sheep-folding or green-manuring are, therefore, very desirable. Frequent repetition is necessary, as the organic matter speedily disappears. Calcium carbonate is often needed and is better applied as ground chalk or limestone than as lime. Potassium salts are beneficial and may be added as kainit; nitrates often give remarkable results, but phosphates are not usually needed because the soil conditions already tend to promote good root development. Only small quantities of manure must be added at the time, as the soil has little retentive power. Above all, no very costly scheme of manuring should be recommended till preliminary trials have shown its profitableness.

In reclaiming or fixing sand dunes the first step is to grow grass, *e.g.* Marram grass (*Psamma*), which will stabilise the form and then allow a more varied vegetation, *e.g.* sand binders (*Carex arenaria*, *Festuca rubra*, *var. arenaria*) and ephemerals, to stabilise the surface, thus leading to the development of a festuca sward or, in other conditions, to heath and scrub.¹

A soil underlain at a short distance below the surface by a bed of gravel, a layer of rock, or a "pan," is liable to be either parched or waterlogged, and its water supply is usually so unsatisfactory that cultivation is unprofitable. Under low rainfall the land becomes a steppe, under rather higher rainfall a heath, but the vegetation is always xerophytic, consisting of heather, ragwort, broom, etc., the trees being birch and conifers—the latter often planted in recent times. No method of cultivating these soils has ever been devised, and most of them still remain barren wastes, defying all attempts at reclamation. Two special cases have, however, yielded to treatment:—

1. When the layer of rock or the pan is only thin and is, in turn, underlain by a rather fine-grained sand, its removal brings about continuity in the soil mass and thus effects a great improvement in the water supply. The soil now resembles the fertile sands, and should be treated in the same way. A good example is afforded by Cox Heath, Maidstone (p. 333).

2. Where the gravel or rock is not too near the surface, systematic green manuring with lupines and other crops fertilised by potassium salts and calcium carbonate will often effect sufficient improvement to make cultivation profitable. Examples are afforded by the Schultz-Lupitz estate, Germany (255), and Dr. Edwards' experiments at Capel St. Andrews, Suffolk, and at Methwold. On such land an industrious cultivator may make a living but not a fortune.

Under favourable conditions recourse may be had to

¹ See F. W. Oliver and E. J. Salisbury, *Topography and Vegetation of Blakeney Point* (Trans. Norfolk and Norwich Nat. Soc., 1913, 9, 485-543)

dressings of clay (as in Lincolnshire) or to warping (in the Fens).

Barren conditions also result when, by reason of a thin parting of clay or its low situation, water cannot run away but accumulates and forms a marsh. Reclamation in such cases is possible as soon as a way out has been found for the water.¹

Loams.—As the proportion of fine material in the soil increases and that of coarse material falls off, a gradual change in the character of the soil sets in, till finally, but without any sharp transition, a new type is reached known as a loam. The increase of fine material somewhat retards the movements both of air and of water, so that loams are characterised by a more uniform water content throughout the mass than sands. On the other hand, loams show less tendency to become water-logged or to allow plants to become parched in very dry weather than clays. The soil decompositions proceed normally, rapidly producing plant food, with little tendency to "sour"² or other abnormal conditions so long as sufficient calcium carbonate is present. In consequence, most plants will grow on loams, even some of those supposed to be specially associated with some other soil type. Thus, where a chalk and a loam soil meet, it is not uncommon to find the chalk plants, *e.g.* traveller's joy (*Clematis Vitalba*), guelder rose, etc., wandering on to the loam, and it is much more difficult to find the line of separation of the soils than where the chalk abuts on to a sand or a clay. For the same reason loams allow of very wide choice in the systems of husbandry, and, as they become very fertile under good management, they are usually in this country all cultivated. Closer observation over a limited area shows, however, that a given class of loam is more suited to one crop than to another; the ecologist recognises differences in the sub-associations or facies, and the practical man will distinguish between a potato soil, a barley soil, a wheat soil, etc.: distinctions due, no doubt, to water

¹ For a fuller discussion of land reclamation see E. J. Russell, *Journ. Roy. Ag. Soc.*, 1919, 80, 112-132.

² See p. 118.

and air relationships, and arising from differences in the compound particles. Unfortunately no method of investigating the compound particles has yet been devised, and a study of the ultimate particles by a mechanical analysis is alone possible. But even though the differences are thus attenuated they can still be traced, as shown by the analysis in Table LXXXII. of soils in Kent, Surrey, and Sussex, known to be well suited to the particular crops.

Low amounts of clay and fine silt, and high amounts of coarse sand, whenever the clay begins to approach 12 per cent., characterise the potato soil; these are the most porous of the series, allowing free drainage and aeration. Barley tolerates heavier and shallower soils. Fruit and hops both

TABLE LXXXII.—MECHANICAL ANALYSES OF SOILS WELL SUITED TO CERTAIN CROPS IN THE SOUTH-EASTERN COUNTIES; LIMITS OF VARIATION. HALL AND RUSSELL (1920).

| | Potatoes. | Barley. | Fruit. | Hops. | Wheat. | Waste Land |
|---------------|-----------|----------|-----------|---------|---------|------------|
| Fine gravel . | 0·1-3 | 0·2-2·5 | 0·3-2·3 | 0·3-2·3 | 0·4-6 | 1-7 |
| Coarse sand . | 2-47 | 1-53 | 0·8-9·5 | 0·7-9·5 | 0-13 | 16-69 |
| Fine sand . | 23-68 | 20-45 | 30-55 | 25-39 | 15-31 | 18-64 |
| Silt . | 3·5-21·4 | 5-33 | 13-44 | 20-45 | 11-35·5 | 2-7 |
| Fine silt . | 5-9 | 3·5-16·4 | 6-11 | 6-11 | 9·5-24 | 2 |
| Clay . | 5·5-12·6 | 4-19 | 10·5-14·6 | 11·5-15 | 13-24 | 1 or less |

require deep soils, and seem to find their most favourable circumstances only in a restricted class of soils: the fruit soils generally contain rather more sand and less silt than the hop soils. But the fruits differ among themselves; the best nursery stock is raised on soils of the potato class, where the conditions are for some unknown reason very favourable to fibrous root development; strawberries prefer the lighter and apples the heavier kinds of fruit soil. Even different varieties of the same plant show distinct preferences for one class of soil over another: the finest varieties of hops are found only on the typical hop soils, and have to be replaced by coarser varieties directly it is desired to grow hops on heavier soils. Preferences for certain soil conditions are also shown by varieties of

the common crops, oats, barley, wheat, etc.; unfortunately these can only be discovered by direct field trials, and even then the results only hold so long as similar conditions prevail and may often be reversed in a different climate or season.

Still more subtle differences may be observed: one and the same variety of a crop will acquire one habit of growth on one soil and a different habit on another. Wheat growing under the best soil conditions will produce stiff straw and ears well set with corn, so that a crop of 50 or 60 bushels per acre may be raised without difficulty; on soil rather different in type, and especially under somewhat different climatic conditions, only 30 or 40 bushels can be raised, because the ears are less thickly set and the straw is too weak to carry a heavier crop, becoming "laid" directly an attempt is made to increase production by increased manuring.¹ Whether some unknown nutrient is absent from these soils, or whether the adjustment of the air and water supply is wrong, is not known; but the limitation of yield arising from this unsuitability of soil conditions is one of the most serious problems of our time. Another instance may be given: in Romney Marsh pastures commonly occur carrying a vegetation of rye grass and white clover, with crested dog's-tail and agrostis, easily capable of fattening sheep in summer without any other food. All round these pastures are others, with *the same type of vegetation*, but the plants grow more slowly, produce more stem and less leaf, are less nutritious and *incapable of fattening sheep*. The soils are identical in mechanical analysis and in general water and temperature relationships, although certain differences have been detected (121*c*). Again: grass grown on Lower Lias pastures in Somersetshire and Warwickshire causes acute diarrhoea ("scouring") in cattle, whilst grass on adjoining alluvial pastures does not (106). Harmful effects of a wholly different nature are recorded from certain Swiss pastures.²

¹ Further illustrations are given by the author in *Science Progress*, 1910, v., 286.

² *Jahrb. Schweiz.*, 1898, 104-5.

Some of the South African grazing lands tend to give the animals a serious disease, Lamziekte, which is attributed to a harmful quality in the herbage and not to any particular plant or organism.¹ Lastly: potatoes grown in the Dunbar district are remarkable for their quality, they will stand boiling and subsequent warming-up without going black. The same varieties of potatoes grown in the same way in the Fens blacken badly under the same treatment, and consequently command a much lower price in the market (7*d*). Instances might be multiplied; enough have been given to show that the plant responds in a remarkable degree to variations in soil conditions. Our knowledge of these variations is fragmentary and wholly empirical, and would be much furthered by close and detailed study, jointly by a botanist and a chemist, of the factors causing differences in plant associations in two nearly similar habitats.

The agricultural treatment of loams, as already indicated, admits of considerable variety. The old plan was to apply a good dressing of dung every third or fourth year and a smaller intermediate dressing; clover was also grown every fourth year, and, on light loams, the root crop was eaten by animals on the land. At long intervals lime was applied and sometimes bones. The modern movement is towards specialisation, each man producing the crops he can best grow and managing them in the way he finds most profitable, but the system usually involves feeding a good deal of imported food to sheep and cattle, either on the land, or in yards, and utilising the excretions as manure, buying nitrate of soda, sulphate of ammonia, and manufacturers' waste products (generally those derived from imported animal or vegetable products) to supply more nitrogen, and buying also imported phosphates and potassium salts. Thus the fertility of highly-farmed countries like England tends to increase at the expense of new countries that export large amounts of animal and vegetable produce. But the transfer is prodigiously wasteful:

¹ See Ingle, *Journ. Agric. Sci.*, 1908, 3, 22-31; A. Theiler, also H. H. Green, *5th and 6th Veterinary Reports, Union of South Africa*, 1918.

enormous losses arise in virgin countries through continuous cultivation (p. 181), and at this end in making dung (p. 193), and especially through our methods of sewage disposal. It seems inevitable that these losses must make themselves felt some day, unless the movement for the conservation of natural resources ever becomes a potent factor in international life.

Soil Fertility and Soil Exhaustion.

From the preceding paragraphs it is clear that fertility is not an absolute property of soils, but has meaning only in relation to particular plants. Plant requirements vary; a soil may be fertile for one plant and not for another; every soil might conceivably prove fertile for something. But in practice the agriculturist can find use only for a very limited number of plants; he, therefore, has to select those combining the double features of saleability in his markets and suitability to his conditions of soil and climate. To a certain extent it is possible to bridge the gap between plant requirements and soil conditions; the former may be permanently altered by breeding if suitable plants cannot be found by selection, and the latter may be changed by such processes as draining, liming, etc. When all has been done that is economically possible there may still remain a divergency between the conditions ideal for the plant and those it finds in the soil; this divergency is the measure of the infertility of the soil for the crop.

The problem has to be simplified by restricting attention to the common agricultural crops and interpreting fertility to mean the capacity for producing heavy crops regardless of any subtle distinctions of quality. Four factors then come into play: an adequate supply of air and water to the roots, a sufficiently rapid production or solution of food material, a sufficiently rapid movement of nutrient substances to the plant roots, and absence of harmful agencies. These have already been discussed in Chapters III. and VI., where also it is shown that the three are not independent, but related to one

another, inasmuch as they are all directly bound up with the nature of the compound particles, and, therefore, with the ultimate particles as revealed by mechanical analysis, and with the amounts of calcium carbonate and of organic matter.

We have seen that the compound particles can be altered considerably by human efforts, within limits fixed by the properties of the unalterable ultimate particles. In trying to improve a soil, therefore, four courses are open:—

1. The water supply may be increased by deepening the soil, *e.g.* by breaking a "pan," by enriching the lower spit, or other device, while the air supply can be increased by drainage.

2. The compound particles may be built up by proper cultivation and the addition of organic matter (*e.g.* dung, green manuring, etc.) and of calcium carbonate.

3. Sufficient calcium carbonate must be added for the needs of the crop and the micro-organisms—nothing but a field trial can determine what this is.

4. The food supply can be increased by the addition of fertilisers, the ploughing-in of green leguminous crops, feeding cake on the land, etc.

Conversely the "exhaustion" of soil is limited in our climate to the removal of organic matter, calcium carbonate, and some of the food (often the nitrogen compounds), and the destruction of the desirable compound particles; the ultimate particles, and all the possibilities they stand for, remain untouched. A distinction is therefore made between the temporary fertility or "condition" within the cultivator's control, and the "inherent" fertility that depends on the unalterable ultimate particles. Of course, the distinction is very indefinite and, in practice, wholly empirical, no proper methods of estimation having yet been worked out, but it is of importance in compensation and valuation cases.

Serious soil exhaustion did not arise under the old agricultural conditions where the people practically lived on the land and no great amount of material had to be sold

away from the farm. Phosphate exhaustion was the most serious occurrence because there was no way of meeting it, and as the original supplies were not as a rule very great, it must have become acute by the end of the eighteenth century in England, for remarkable improvements were, and still are, effected all over the country by adding phosphates. Then began a process, which has gone on to an increasing extent ever since, of ransacking the whole world for phosphates; at first the search was for bones, even the old battle-fields not being spared, if we may believe some of the accounts that have come down; later on (in 1842) Henslow discovered large deposits of mineral phosphates, to which more and more attention has been paid. Phosphate supplies may yet become the factor that will determine the course of history.

The crowding of the population into cities, and the enormous cheapening of transport rates, led during the nineteenth century to the adoption in new countries, particularly in North America, of what is perhaps the most wasteful method of farming known: continuous arable cultivation without periodical spells of leguminous and grass crops. The organic matter was rapidly oxidised away, leaching and erosion increased considerably when the cover of vegetation was removed, while the compound particles that had slowly been forming through the ages soon broke down. Nothing was returned to the soil, the grain and other portable products were sold and the straw burnt. The result has been a rate of exhaustion unparalleled in older countries, and wholly beyond the farmer's power to remedy, consequently he left the land and moved on. The excellent experimental studies of Hopkins (138) at the Illinois Experimental Station, of Whitson (307) at Wisconsin, and other American investigators, have shown that additions of lime, of phosphates, and sometimes of potassium salts, with the introduction of rotations including grass and leguminous crops, and proper cultivations will slowly bring about a very marked improvement.

CHAPTER IX.

SOIL ANALYSIS AND ITS INTERPRETATION.

WHEN an agricultural chemist is asked to analyse a soil he is expected to give some information about the crops to which it is best suited, and the manures that must be applied; he has, therefore, a much more complex problem than the mineralogical or geological chemist who simply has to report on the actual constituents he finds. It has been shown in the last chapter that the vegetation relationships of soils are not determined solely by the nature of the soil, but also by its position, subsoil, climate, and other circumstances, so that it is manifestly impossible for the chemist to make a satisfactory report on a sample of soil on the basis of analytical data only. He cannot even give a complete account of the soil itself, since he has no method of estimating the compound particles on which the water and air supply, the temperature and the cultivation properties depend, but he can only get at the ultimate particles out of which they are built.

Soil analysis is, therefore, restricted to: (1) comparisons between soils, showing which are fundamentally identical and in what respects others differ; (2) the tracing of such correlations as exist between the chemical and physical properties of the soils of a given area and the crops and agricultural methods generally associated with them. In order to carry out either of these satisfactorily it is necessary to make a systematic soil survey, a task that is certainly laborious but by no means impossible, since each agricultural chemist usually confines his attention to a definite region—a county or so—and is not called upon to deal with outside soils.

In planning a soil survey it must be remembered that the

basis of the whole work is empirical: the agricultural and vegetation characteristics have first to be ascertained by field trials, and then systematised and amplified by aid of the laboratory data. It is necessary to begin, therefore, by going over the whole region very carefully and dividing it up in areas within which similar agricultural or vegetation characteristics prevail. In general the areas differentiated in the geological drift maps will be found identical with the vegetation areas, especially if the drift map is interpreted in the light of the *Memoirs of the Geological Survey*. But as agriculture is influenced by altitude and rainfall, the investigator must also use an ordinary contour map and a rainfall map, which, unfortunately, he must construct for himself from data in *British Rainfall*. Within each vegetation area a number of soil samples must then be taken from points representing the area as closely as possible: situated, for example, on level regions or long gentle slopes, and not on made ground, steep slopes, or places of local disturbance, etc.

In seeking for typical places the investigator is likely to meet with a good deal of discouragement; farmers will tell him that half a dozen or more different kinds of soil occur on their particular farms, while the vegetation of a wild area may show considerable changes. But these differences often arise from differences in the compound particles and not in the ultimate particles; small variations in the amount of calcium carbonate or of organic matter, or differences in the water supply, or management, may considerably affect the ease of cultivation and the vegetation relationships and give the impression of a wholly different type of soil. So little does cropping, cultivation, etc., affect the ultimate particles that it is quite immaterial for the purpose of a soil survey whether the sample is taken from pasture land or arable land, but it is well to take a number of samples from both. With a little practice abnormal places are easily avoided. It is necessary to take a large number of samples, not only to get at the type, but also to trace out the causes of the phenomena noted by the farmer, and to discover the main factors determining the cultivation

and vegetation relationships of the soil. Very full inquiries must be made on the spot as to the agricultural value of the land, the crops and manures most suitable, its behaviour during drought and wet weather, and any special points to be observed during cultivation. Information is also wanted about the most troublesome weeds, the native vegetation, hedgerow and other timber, etc., and note must be taken of the position of the soil in regard to water supply, the nature of the strata down to the permanent water table, etc. The most reliable information is obtained only by properly conducted manurial trials.

It is usual to take the sample to a depth of 9 inches and a lower sample to a depth of 18 inches, but if any marked change occurs in the soil the sample should only be taken to the point where it sets in. The subsoil sample does not characterise the formation any better than the surface sample, but it affords a useful check and helps in detecting abnormalities.

The vegetation areas correspond with the geological formations only so long as the lithological characters remain constant. Some formations are very uniform, *e.g.* the Folkestone beds of the Lower Greensand, but, in general, certain changes are observed. Where the formation has been laid down in an estuary of no very great size, the coarser particles are deposited near the old shore and the finer particles farther out, so that a gradual change from finer to coarser soil is observed in travelling along the formation, necessitating a soil division into two or three vegetation areas; the Hythe beds of the Lower Greensand and the London clay afford illustrations. Considerable trouble often arises when the formation consists of a number of strata of sands and clays, and the outcrops are so narrow that no one type persists over any large area. The simplest method of procedure is to map out any uniform areas that possess sufficient agricultural importance, and then group the remaining less important soils simply into gravels, sands, loams, and clays. In dealing with drift soils, it is well first to map the uniform areas and then look out for lines of uniformity and make up regions within which the agricultural character-

istics vary between a higher and a lower limit. The investigator must be guided by the importance of the region from the particular point of view in deciding how closely he is to map out the country.

Absolute uniformity cannot be expected over any considerable area, and even such uniformity as existed has often been upset by subsequent rearrangements of the soil which result in the original surface being covered up with a later deposit or being washed away, leaving the original subsoil to become the new soil. Such changes are readily detected by mechanical analysis of the surface and subsoils; examples are given in Table LXXXIII. At Merton the subsoil on the lower ground appears to have been the original surface soil, because of its identity with the surface soil and its marked difference from the subsoil of the land higher up; it has been covered with a deposit identical with and presumably derived from the higher lying soil. The same thing has happened at Hamsey Green. At Woodchurch, however, it appears that the old surface of 69, now the subsoil, has been covered with rather a lighter soil; it is equally possible, however, in this particular case that 70 has lost its original surface soil, the present

TABLE LXXXIII.—VARIATION IN SOIL DUE TO WASHING OR FLOODING.

| Formation | London Clay. | | | | Clay-with-Flints. | | | | Weald. | | | |
|-------------|-----------------|----------|--------------|----------|-----------------------|----------|---------------------------|----------|-------------------|----------|----------|----------|
| Locality | Merton, Surrey. | | | | Hamsey Green, Surrey. | | | | Woodchurch, Kent. | | | |
| | Lower Ground. | | On the Hill. | | Soil 109. | | Soil 110, 200 yards away. | | Soil 69. | | Soil 70. | |
| | Surface. | Subsoil. | Surface. | Subsoil. | Surface. | Subsoil. | Surface. | Subsoil. | Surface. | Subsoil. | Surface. | Subsoil. |
| Fine gravel | 1'7 | 1'3 | 1'5 | 0'3 | 1'6 | 3'1 | 1'7 | 1'4 | 0'5 | 0'6 | 0'9 | 0'7 |
| Coarse sand | 18'4 | 23'6 | 16'9 | 8'4 | 9'5 | 6'7 | 5'3 | 7'1 | 2'5 | 1'9 | 1'1 | 1'1 |
| Fine sand | 12'7 | 11'3 | 12'4 | 12'7 | 22'3 | 28'0 | 20'7 | 25'1 | 14'7 | 13'0 | 9'3 | 9'0 |
| Silt | 16'6 | 18'0 | 16'6 | 13'4 | 25'4 | 22'5 | 26'3 | 17'6 | 24'2 | 27'8 | 25'9 | 18'8 |
| Fine silt | 11'1 | 11'4 | 10'1 | 9'8 | 9'9 | 12'6 | 10'2 | 9'5 | 23'7 | 23'3 | 24'4 | 26'5 |
| Clay | 24'6 | 24'9 | 26'7 | 41'7 | 16'0 | 16'4 | 16'4 | 28'3 | 20'1 | 28'9 | 28'6 | 37'8 |

surface being the bared subsoil. This kind of variation is common on clay soils and often leads to differences in agricultural value that are fairly marked, but not sufficient to affect the type. Normally the subsoil contains more clay than the surface soil (as in 110, 69, and 70), and any deviation should be carefully investigated.

The characterisation of soil types is usually effected by mechanical analysis and determinations of calcium carbonate and organic matter. A representative set of soils should, however, be subjected to chemical analysis, the clay fractions being, if possible, broken up by ammonium fluoride and analysed completely. Soils about which precise information has been obtained by manurial and other trials should be very completely examined in order that they may serve as standards in the analysis of other soils from the same area.

The problem set by the farmer is wholly different. He does not want to know to what type his soil belongs, but how he must manure it, etc. If the analyst has an adequate knowledge of the soil type and the locality he can readily ascertain in what respects the soil differs from the type, and then, from the known results of manurial and other trials on that type, he can give the information wanted with a reasonable degree of probability; otherwise his report can only be a matter of guesswork. In short, the farmer's problem can be satisfactorily solved, and the manurial trials fully interpreted, only when a complete soil survey has been made.

The analyst must consider the soil from three points of view: (1) its physical properties, especially those relating to the ease of movement of the soil water; (2) its store of plant food, actual and potential; (3) the rate at which potential food can be converted into actual food.

The Interpretation of Mechanical Analyses.¹

The properties of the various fractions have already been given in Chapter III., but some little practice is necessary

¹ See Appendix for Methods of Analysis and pp. 98 and 102 for details as to dimensions and composition of fractions.

before they can be used for the interpretation of an analysis. A few illustrations are therefore given from Hall and Russell's survey of Kent, Surrey, and Sussex (121*a*): the data are set out in Table LXXXIV.

The Chilworth soil contains so little clay and fine silt and so much coarse sand that it has very little power of retaining water. As it lies too high to obtain any seepage water from the neighbouring formations it is dependent on the immediate rainfall, and is therefore not in cultivation but has always been heath land. Owing to its bad constitution and its high situation it could not by any known method be made suitable for farming.

TABLE LXXXIV.—MECHANICAL ANALYSES OF SOILS AND THEIR INTERPRETATIONS.

| Formation | Folkestone Beds. | | Thanet Beds. | | Brick Earth. | | London Clay. | Weald Clay. | Alluvium. | |
|-------------------|------------------|-----------|--------------|----------|--------------|--------|--------------|--------------|-----------|------|
| Locality | Chilworth. | Shalford. | Goldstone. | Barnton. | ickham. | Oving. | Tolworth. | Shadoxhurst. | Ewhurst. | |
| Gravel | 1.2 | 2.5 | 0.2 | 0.2 | 0.3 | 0.9 | 0.4 | 0.2 | 0.7 | 0.1 |
| Coarse sand | 65.9 | 52.6 | 15.3 | 2.3 | 0.7 | 1.3 | 12.8 | 1.5 | 1.0 | 0.5 |
| Fine sand | 23.7 | 26.2 | 14.9 | 34.7 | 4.7 | 16.0 | 25.5 | 11.0 | 19.8 | 19.3 |
| Silt | 2.4 | 4.8 | 17.3 | 36.2 | 14.8 | 35.8 | 11.3 | 19.6 | 28.4 | 13.0 |
| Fine silt | 2.0 | 3.5 | 6.3 | 6.3 | 8.6 | 14.3 | 11.1 | 26.8 | 12.1 | 20.0 |
| Clay | 0.9 | 3.8 | 8.9 | 11.5 | 14.7 | 15.9 | 23.7 | 22.1 | 19.7 | 26.9 |
| Calcium carbonate | nil | 0.3 | 0.08 | 0.18 | 0.4 | 0.75 | 2.0 | 0.16 | 0.05 | 0.28 |
| Loss on ignition | 2.6 | 3.3 | 3.1 | 4.3 | 4.6 | 6.5 | 5.6 | 9.8 | 10.2 | 11.3 |

The Shalford soil lies lower down and has a better water-supply, less coarse sand, and more clay and fine silt. But its water-holding capacity and its retentive power for manures are still very low; artificial manures are of much less value than organic manures, and the best treatment of the land is to grow green crops and fold them off to sheep. It is better suited to special purposes like the production of malting barley or market-garden crops than to ordinary mixed farming.

The Goldstone soil contains more clay and fine silt, and

has therefore better power of retaining water and manures, and is more productive and more generally useful. But as the coarse sand exceeds the clay in amount it is still distinctly light; it responds better to organic than to artificial manures and suffers rather in drouthy weather in spite of lying not far above the marshes. It contains 45 per cent. of fine sand and therefore tends to cake on the surface after rain and to form steely lumps if worked when wet. Under proper management, however, it produces good crops and is equally suited for ordinary arable and for fruit or potato cultivation.

The next three soils may be taken as illustrations of the very best loams in the three counties. Silt forms the largest fraction and therefore the soils possess sufficient, but not too great, a power of retaining water. The fine silt is always lower than the clay; the latter varies between 12 and 16 per cent., a very satisfactory amount where the rainfall is not too high. As there is a considerable amount of fine sand and no excess of fine silt and clay, the absence of coarse sand is no disadvantage.

The Tolworth soil is highly productive arable land but almost too heavy for profitable cultivation; only by dressings of dung (fortunately obtainable cheaply from town) can it be kept workable. It contains rather too much clay and would no doubt have gone down to grass had there not been so much coarse sand present.

The Shaddoxhurst soil is bad. It contains much clay and still more fine silt, consequently its texture is not improved as much as might be expected by liming. There is practically no coarse sand and not much fine sand to keep the soil open, it has always and deservedly been in bad repute. It is best as pasture land, and, after drainage and treatment with basic slag, it may be made useful but never very good.

The Ewhurst soils are both in pasture, being too heavy for arable cultivation on account of their high clay and low coarse sand content. The first has the better constitution: silt is the predominant feature, the clay is not too high, nor is the fine silt. It has all the characteristics of a good, heavy.

soil, and is indeed known to be an excellent bullock pasture. The second is not so good; it contains too much clay and fine silt, and too little silt and coarse sand. It has no great agricultural value.

Factors Modifying the Interpretation of a Mechanical Analysis.

The Amount of Organic Matter.—Organic matter at the proper stage of decomposition has the effect of binding a loose soil and lightening a heavy one; thus it reduces the difference between a light sand and a heavy clay, bringing them both closer to the loams. When 10 to 15 per cent. of organic matter is present it so impresses its properties on the soil that the mechanical analysis loses much of its significance, and all the analyst can do is to point out what the soil would become if by persistence in certain methods of management the organic matter were reduced below a certain point.

It is, however, essential that the organic matter should be properly decomposed. Barren sandy wastes not infrequently contain 5 to 10 or even 15 per cent. of organic matter, but much of it is simply dried bracken or other vegetation that has not broken down and has no value, but rather the reverse, in improving the physical conditions. If the drainage is bad a good deal of peat may form; further, the water fills up the soil, making its condition bad whatever its composition may be.

The Amount of Calcium Carbonate.—In interpreting a mechanical analysis it must be remembered, as shown on p. 117, that 1 or 2 per cent. of calcium carbonate may greatly modify the clay properties and give a considerable degree of friability to a soil which otherwise would be very intractable. When the percentage rises to much higher amounts the soil becomes very chalky and the mechanical analysis loses its meaning, just as when much organic matter is present.

Water-supply and the Interpretation of Mechanical Analysis.

It has already been pointed out that a mechanical analysis can be interpreted and discussed with any degree of

completeness only in terms of the water-supply; the rainfall, the coolness of the climate, the presence of moving underground water, and the nature of the subsoil all have to be taken into account.

Effect of the Rainfall.—The effect of a high rainfall is to bring into prominence the “sticky” properties of the fine fractions, and to put into the background their water-holding capacity. Thus a light soil under a high rainfall behaves like a heavier soil under a low rainfall; it is as well supplied with water and on the whole behaves in the same kind of way on cultivation. For example, the Stedham soil (Table LXXXV.) is rather lighter than the Swanley soil, and yet in virtue of its extra rainfall is more useful for farming purposes; indeed, the Swanley soil is essentially a market-garden soil, requiring large dressings of dung for successful cultivation. The North Chapel soil is physically as good as the East Farleigh soil but agriculturally much inferior; owing to the higher rainfall it becomes somewhat too sticky to cultivate profitably and so is in rather poor grass; the East Farleigh soil, on the other hand, is from a highly fertile hop garden.

TABLE LXXXV.—WATER-SUPPLY AND INTERPRETATION OF MECHANICAL ANALYSIS.

| | Swanley, Stedham. | | North Chapel. | East Farleigh. | Tol-worth. | Nut-field. | Dunbar. | |
|------------------------------------|-------------------|------|---------------|----------------|------------|------------|---------|------|
| Fine gravel . . . | 1'2 | 1'4 | 0'9 | 2'3 | 0'6 | 2'9 | 3'0 | 1'0 |
| Coarse sand . . . | 10'2 | 9'3 | 11'4 | 9'5 | 37'8 | 46'6 | 33'5 | 43'7 |
| Fine sand . . . | 58'6 | 68'5 | 43'2 | 30'6 | 33'1 | 22'9 | 28'0 | 38'2 |
| Silt . . . | 13'3 | 3'6 | 13'0 | 19'7 | 7'7 | 3'5 | 5'5 | 6'8 |
| Fine silt . . . | 5'1 | 5'6 | 10'2 | 11'1 | 4'7 | 8'8 | 10'8 | 11'8 |
| Clay . . . | 5'5 | 5'5 | 10'9 | 13'3 | 7'6 | 6'9 | 6'6 | 9'5 |
| Loss on ignition . | 2'9 | 3'4 | 5'1 | 5'6 | 3'6 | 3'6 | 6'9 | 6'2 |
| Calcium carbonate | '02 | '03 | '80 | 1'0 | '27 | '21 | '15 | '31 |
| Rainfall in inches (approximate) . | 24 | 33 | 30 | 24 | 28 | 27'5 | 25 | 25 |

Coolness of Climate.—Soils containing so much coarse sand or fine sand that they would scorch or burn in a dry warm

¹ An example is given by G. W. Robinson, *Journ. Ag. Sci.*, 1917, 8, 370.

district may prove very suitable for cultivation in a cooler district where evaporation is lessened. Potato soils afford some good illustrations; potatoes require a light soil, but it must be cool and moist. The Nutfield soil (Table LXXXV.) fulfils these conditions; it is on a slope facing northwards not very far above a stream, and, therefore, does not quickly dry out, hence it is very good for main crop potatoes. The Tolworth soil, on the other hand, although similar in composition, is so placed that it quickly dries and is of much less value. Some of the potato soils of Dunbar, analysed by S. F. Ashby (7*d*), have all the appearance of soils readily drying out, but in their cool climate this property does not show itself to an injurious extent.

Effect of Underground Water.—When the underground water is near the surface, but sufficiently far below to allow of proper root development, the most important property of the soil becomes its power of lifting the water by surface action up to the roots. The silt and sands are in such cases the useful constituents, the clay and fine silt being less necessary. The Weybridge soil (Table LXXXVI.), at about 3 feet below its surface, has a current of underground water which is brought to the roots by the fine and coarse sand. It therefore grows excellent wheat crops. The Bagshot sands, however, although similar in physical type, have in general no such water-supplies and are sterile because they lack the clay which, in their circumstances, could alone confer an adequate power of holding water from one shower to the next.

TABLE LXXXVI.—UNDERGROUND WATER AND MECHANICAL ANALYSIS.

| | Weybridge. | Bagshot Beds. | Shalford. | Lydd. |
|-------------------|------------|---------------|-----------|-------|
| Fine gravel . . . | 1·3 | 11 to 16 | 2·5 | 6·1 |
| Coarse sand . . . | 38·4 | 20 „ 30 | 52·6 | 6·9 |
| Fine sand . . . | 39·9 | 45 „ 65 | 26·2 | 66·7 |
| Silt . . . | 5·6 | 5 „ 10 | 4·8 | 7·2 |
| Fine silt . . . | 5·1 | 5 „ 10 | 3·5 | 11·4 |
| Clay . . . | 3·8 | 3 „ 7 | 3·8 | 3·9 |

The Shalford soil is a light sand with too little power of

retaining water for pastures to last through a hot summer, consequently the grass land, except near the brooks, is parched and scorched. The Lydd soil is certainly somewhat finer grained, but not so very different that one would expect to find it much better for pasture purposes, yet it produces one of the best pastures in Romney Marsh, not only carrying but fattening sheep throughout the summer. It has, however, a constant supply of water 3 or 4 feet below the surface, while at Shalford the water level is much lower down.

This underground flow is one of the factors concerned in the proverbial fertility of valleys. Soils lying towards the bottom of a long slope receive not only the rainfall but also the water steadily drifting downwards to the stream or marsh at the bottom, and this advantage is further enhanced by the gradual transport of soil down the slope which increases the depth through which the plant roots can range.

Effect of the Subsoil.—In general the subsoil is rather heavier in type than the surface soil, especially in the case of clays; examples are given in Table LXXXVII. The exceptions to this rule may arise through periodical flooding with water containing much clay in suspension, or through the occurrence of a bed of sand just below the surface.

TABLE LXXXVII.—NATURE OF THE SUBSOIL.

| | Loddington. | | Harting. | | Dicker. | | Shopwyke. | | Wye. | |
|-------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|
| | Sur- face. | Sub- soil. | Sur- face. | Sub- soil. | Sur- face. | Sub- soil. | Sur- face. | Sub- soil. | Sur- face. | Sub- soil. |
| Fine gravel | 3'5 | 2'6 | 0'6 | 0'2 | 1'0 | 0'6 | 0'6 | 0'1 | 1'0 | 0'2 |
| Coarse sand | 10'2 | 9'8 | 3'3 | 3'2 | 2'0 | 1'1 | 0'8 | 0'4 | 3'0 | 1'9 |
| Fine sand | 33'5 | 30'2 | 31'6 | 33'9 | 26'6 | 23'2 | 25'0 | 21'9 | 27'2 | 25'3 |
| Silt | 14'6 | 17'5 | 17'3 | 21'3 | 23'0 | 15'1 | 27'3 | 38'0 | 40'0 | 41'4 |
| Fine silt | 14'9 | 15'5 | 14'5 | 13'4 | 17'8 | 21'9 | 16'4 | 15'2 | 8'9 | 9'6 |
| Clay | 12'2 | 15'3 | 12'3 | 16'0 | 17'9 | 25'7 | 11'1 | 15'7 | 11'2 | 14'5 |

Two cases described on page 314 may be illustrated here. The bad effect of a layer of impermeable material near the surface is shown by the Loddington soil (Table LXXXVII.).

typical of an area near Maidstone (Cox Heath), much of which was waste land. Its sterility was due to no fault in the soil, which is obviously of excellent type, but to a thin layer of rock lying near the surface. When this was removed a very good soil was obtained. The Harting soil lies on the Upper Greensand in West Sussex; the rock comes close to the surface, restricting both the root range of the plant and the water supply where it lies horizontally, but proving much less harmful where it dips at any considerable angle. The soil itself is good, although it has rather too much fine silt, and it becomes very productive when the effect of the rock is counteracted. The Dicker soil, while not of the best type, as its fine silt is too high, is far from being hopeless, but it unfortunately lies on a deep bed of stiff clay which keeps it wet in winter and parched in summer. It is therefore very poor, and even with the best management never gives great results.

The second case, over-drainage, is illustrated by the Shopwyke soil in the same table. It is a fair soil, containing too much fine silt to be in the first rank, but it is spoiled by lying on a deep bed of gravel only nine inches or a foot below the surface—the subsoil sample could only be taken in one or two instances. Consequently it dries out badly in summer and does not repay much expenditure in the way of manures.

The Wye soil is given as an instance of the normal case where a soil becomes rather heavier in its lower depths, with the result that the movement of water is somewhat impeded without being stopped. Thus the subsoil furnishes a reserve of water for the surface, yet even in wet weather it does not hold up too much water. The Wye soil contrasts with the Dicker soil, the usual case in a clay, where the subsoil contains much more true clay than the surface.

Chemical Analysis of Soils.¹

Recourse is had to chemical analysis to discover the amounts of potential and actual plant food in the soil, and the

¹ See Appendix for methods of analysis.

rate at which potential food is likely to become available. But as the problem is vague, so the methods are empirical and the interpretation of the results often very difficult.

The following discussion is confined to English soils and English methods. No claim is made that these methods are superior to those of other countries or that they give absolute information about the amounts of plant nutrients in soils. They are intended only to facilitate comparison of given soils with a standard soil, and they are probably neither better nor worse than other analytical methods which might be proposed.

In the United States chemical analysis is not in much favour with the younger school of investigators, though determinations are made of the components of the water extracts of soils.¹

For a discussion of the chemical and physical properties of soils formed direct from granite in Aberdeen, or from the paleozoic soils of North Wales, the reader is referred to the papers by Hendrick and Ogg (132)² and G. W. Robinson (240).

Organic Matter.—The analyst should note whether the organic matter is fairly well decomposed, whether it still shows definite plant structure, and whether or not it is acid to litmus paper. He can then interpret his observations as shown on pages 128 *et seq.*

Nitrogen.—Unlike the other soil constituents nitrogen and carbonates are determined absolutely. The amount of nitrogen is closely related to the loss on ignition, of which in a large proportion of cases it is about 3 per cent. As a guide to fertility it is therefore subject to the same limitations; a high nitrogen content may be associated either with a rich soil containing abundance of valuable non-acid organic matter.

¹ See, e.g., J. S. Burd, *Journ. Agric. Res.*, 1918, 12, 297-310, and *Soil Sci.*, 1918, 5, 405-419, who finds water more useful than citric acid and holds hydrochloric acid worthless as a means of assessing the crop producing power of a soil (see p. 234).

² See also *Aberdeen Bulls.*, 1, 3, and 10, where the relationship between soil analysis and manurial results is discussed.

or with a soil where the conditions are so unfavourable that organic debris does not decompose (*e.g.* acid soils), or only forms accumulations of peat. On the other hand, some of the best loams, where the conditions are most favourable to rapid decomposition and nitrification, contain but little nitrogen. A few typical examples are given in Table LXXXVIII.

TABLE LXXXVIII.—NITROGEN AND LOSS ON IGNITION.

| | Fertile Arable Soils. | | | | Poor Arable Soils. | | | | Barren Wastes. | | |
|-----------------------------|-----------------------|------|------|------|--------------------|------|------|------|----------------|------|------|
| Loss on ignition | 4·65 | 6·58 | 3·70 | 4·65 | 4·13 | 6·23 | 3·60 | 5·14 | 5·94 | 7·00 | 5·81 |
| Nitrogen . . . | ·120 | ·220 | ·133 | ·141 | ·128 | ·143 | ·182 | ·152 | ·130 | ·195 | ·167 |
| Loss on ignition in subsoil | 3·00 | 4·94 | 2·81 | 3·29 | 3·74 | 5·50 | 2·58 | 4·14 | — | — | 2·70 |
| Nitrogen in sub-soil . . . | ·078 | ·139 | ·081 | ·097 | ·112 | ·104 | ·061 | ·096 | — | — | ·058 |

Soils containing much calcium carbonate are as a rule rich in nitrogen, partly no doubt because of the rather high nitrogen content of the rock and partly also because they are folded, green manured, cropped with leguminous plants like sainfoin, lucerne, etc., all of which tend to increase the nitrogen supply. The nitrogen in some chalk soils is given in Table LXXXIX.; all are arable soils, excepting the last, which is open downland.

TABLE LXXXIX.—NITROGEN CONTENT OF CERTAIN CHALK SOILS.

| | | | | | | |
|---|-------|------|------|------|------|------|
| Nitrogen in surface soil . . . | ·25 | ·194 | ·331 | ·258 | ·249 | ·419 |
| „ subsoil . . . | ·128 | ·130 | ·162 | ·192 | ·196 | ·180 |
| Calcium carbonate in surface soil . . . | 18·1 | 3·70 | 49·7 | 66·0 | 65·6 | 44·0 |
| Calcium carbonate in sub-soil . . . | 11·37 | 14·9 | 61·3 | 55·2 | 54·8 | 71·6 |

Carbonates.—The analyst is often asked whether or not a particular soil contains sufficient calcium carbonate, and in endeavouring to answer this question he must bear in mind the twofold function of this substance, to prevent “sourness” (*p.* 118), and to flocculate the clay. Where only a small amount of clay—say 8 per cent. or less—is present the flocculating action is less needed and a smaller amount of calcium

carbonate suffices. The Stedham soil (Table LXXXV.) is an example; it is near the bottom of a slope along which water containing calcium bicarbonate in solution is drifting, and therefore shows no tendency to become sour. The 0·03 per cent. of calcium carbonate present, hopelessly inadequate as it appears, suffices for its needs and no increase in crop is obtained by applying lime. The Lydd soil (Table LXXXVI.) contains only 0·02 per cent., but is also well supplied with calcareous water from below and shows no sign of sourness. Similar soils that have not this advantage of position stand in great need of lime even when 0·1 per cent. is present. As the amount of clay increases, the need for lime becomes greater because flocculation is now wanted; soils with 20 per cent. or more of clay may need two or three times as much lime as sandy soils. It is impossible to fix limits that shall hold universally. Some soils free from lime appear to need none: Hendrick and Ogg's Craibstone soil has already been mentioned (p. 118). Grégoire¹ also found soils practically free from carbonate and yet not acid, and presumably not needing lime. Before an analyst recommends lime or chalk on a sandy soil he should satisfy himself that the need is indicated by the vegetation, and before he states that lime is not necessary on a clay he should be quite sure that further additions would have no beneficial flocculating effect. The need of lime is indicated:—

1. If clover fails to start well, or to stand the winter, or if it looks bad in spring.

Cases have been examined by the writer where clover or lucerne were failing in patches in the field and weeds were consequently getting a firm hold. The amounts of lime in the soil were —

On the good parts: Suffolk lucerne, 0·8, Norfolk lucerne, 0·6,
Herts clover, 0·2 per cent. calcium carbonate.

On the bad patches: Suffolk lucerne, 0·07, Norfolk lucerne, 0·2,
Herts clover, 0·01 per cent. calcium carbonate.

2. If swedes, turnips, or cabbages get finger-and-toe rather badly.

The Armstrong College experiments have shown that 2 tons per acre of ground lime, or $3\frac{1}{4}$ tons per acre of ground limestone, afford suitable dressings in this case.¹

3. If mayweed springs up vigorously among the wheat, or if spurrey, sorrel, or bent grass become prevalent.

Land that has been wet through the winter ought to have lime in the spring: otherwise uneven patches may arise in the field on which weeds develop and the crop ripens unevenly.

Neither lime nor limestone, however, should be applied to potatoes or oats unless actual trials have shown that benefit will be obtained; as a general rule these two crops respond less than others: and in the Kilmarnock trials,² lasting over eight years, potatoes were actually injured by lime, though oats benefited by it (p. 244).

Basic slag reduces the need for lime, but superphosphate does not. Sulphate of ammonia increases the need for lime. Instances of soils known to respond to lime are given in Table XC.

TABLE XC.—CALCIUM CARBONATE CONTENT OF SOILS KNOWN TO RESPOND TO LIME.

| Sandy Soils. | | | Loams and Clays | | |
|---------------------------|---------------------|----------------------------------|---------------------------|---------------------|----------------------------------|
| No. of Soil. ³ | Percentage of Clay. | Percentage of Calcium Carbonate. | No. of Soil. ³ | Percentage of Clay. | Percentage of Calcium Carbonate. |
| 126 | 7·8 | ·04 | 207 | 11·1 | ·02 |
| 675 | 8·9 | ·08 | 119 | 10·4 | ·03 |
| 193 | 6·0 | ·18 | 118 | 11·5 | ·18 |
| 189 | 3·8 | ·35 | 152 | 12·2 | ·26 |
| | | | 215 | 13·0 | ·45 |
| | | | 127 | 13·3 | 1·00 |

¹ Armstrong Coll. Bull., No. 12, 1915.

² West of Scotland Agric. Coll. Bull., No. 55, 1911 (pp. 193-222).

³ The numbers are those used in *Soils and Agriculture of Kent, Surrey, and Sussex* (Hall and Russell).

Alumina.—In general, in the much weathered soils of the south of England the alumina is approximately equal in amount to one-third of the clay fraction, indicating that the acid treatment breaks down some definite group of silicates associated mainly with the clay fraction in the soil.² Examples are given in Table XCI.

TABLE XCI.—ALUMINA AND CLAY CONTENTS OF VARIOUS SOILS.

| Formation. | Bagshot Sands. | | | London Clay. | | Thanet Beds. | | Sandgate Beds. | Folkestone Beds. | Weald Clay |
|---|----------------|------|------|--------------|------|--------------|------|----------------|------------------|------------|
| Percentage of clay in soil . . . | 3·6 | 4·9 | 7·1 | 36·8 | 21·3 | 11·5 | 7·1 | 15·3 | 6·9 | 33·8 |
| Percentage of Al_2O_3 in soil . . . | ·92 | 1·43 | 1·94 | 11·75 | 6·78 | 3·46 | 2·66 | 5·14 | 1·99 | 10·45 |
| Ratio $\frac{\text{Al}_2\text{O}_3}{\text{clay}}$. . . | ·25 | ·29 | ·27 | ·31 | ·31 | ·31 | ·37 | ·33 | ·28 | ·31 |

Exceptions to the rule occur when much fine silt is present, the alumina then being markedly less than one-third of the clay (Table XCII.).

TABLE XCII.—ALUMINA AND CLAY CONTENTS OF SILTY SOILS.

| Formation. | Weald Clay. | | | Lower Wealden Beds. | | | Upper Greensand. | Gault. |
|---|-------------|------|------|---------------------|------|------|------------------|--------|
| Percentage of fine silt in soil . . . | 27·4 | 35·8 | 25·9 | 15·8 | 21·5 | 14·3 | 15·9 | 14·5 |
| Percentage of clay in soil . . . | 21·5 | 22·1 | 19·4 | 5·4 | 12·5 | 9·7 | 13·1 | 12·3 |
| Percentage of Al_2O_3 . . . | 5·02 | 5·42 | 5·68 | ·17 | 1·66 | 2·38 | 2·48 | 2·39 |
| Ratio $\frac{\text{Al}_2\text{O}_3}{\text{clay}}$. . . | ·23 | ·25 | ·29 | ·03 | ·13 | ·24 | ·18 | ·19 |

Iron Oxide.—The iron oxide is present in quantities comparable with those of alumina, but no close relationship is observable, nor does the amount of iron oxide afford any indication of the fertility of the soil. F. V. Dutton finds no more iron in the fertile red soils of Devon than in the infertile grey soils. Light soils, good or bad, contain about 1 to 2·5

² The percentage of Al_2O_3 given here represents the amounts extracted by HCl and are not comparable with those on p. 102 obtained after treatment with ammonium fluoride.

per cent., good loams and poor clays contain 3·5 to 5 per cent. Larger amounts of iron oxide are not common. Soils containing ferrous compounds are generally infertile.¹

Lime and Magnesia.—About ·1 to ·5 per cent. of magnesia is found in the soils we have examined, and in general the ^{lime} _{magnesia} ratio falls between 1 and 3, but ratios of 4 and 5 are not uncommon, while on chalk soils they may rise very high. No connection could be traced between the ^{lime} _{magnesia} ratio and the productiveness of the soil; indeed, Table XCIII. shows that very good and very poor soils may have practically identical ratios.

TABLE XCIII.—^{LIME} _{MAGNESIA} RATIO IN VARIOUS SOILS.

| Barren Wastes. | | | | Poor Cultivated Soils. | | | | Fertile Soils. | | | |
|----------------|------|------|---------------|------------------------|------|------|---------------|----------------|------|------|---------------|
| No. of Soil. | CaO. | MgO. | Ratio CaO MgO | No. of Soil. | CaO. | MgO. | Ratio CaO MgO | No. of Soil. | CaO. | MgO. | Ratio CaO MgO |
| 170 | ·05 | ·06 | 1·0 | 45 | ·43 | ·23 | 1·9 | 183 | ·56 | ·40 | 1·4 |
| 192 | ·13 | ·08 | 1·6 | 242 | ·30 | ·13 | 2·3 | 222 | ·46 | ·28 | 1·6 |
| 168 | ·21 | ·13 | 1·6 | 106 | ·48 | ·21 | 2·3 | 152 | 1·02 | ·41 | 2·5 |
| 50 | ·15 | ·08 | 1·9 | 255 | ·80 | ·27 | 3·4 | 122 | ·60 | ·22 | 2·7 |
| 197 | ·21 | ·08 | 2·6 | 196 | ·43 | ·12 | 3·6 | 211 | 1·79 | ·40 | 4·5 |
| 91 | ·08 | ·03 | 2·7 | 287 | 1·19 | ·29 | 4·0 | 72 | 1·94 | ·42 | 4·6 |
| 241 | ·22 | ·07 | 3·1 | | | | | 127 | 2·14 | ·40 | 5·4 |
| 13 | ·58 | ·14 | 4·1 | | | | | | | | |

Potash.—In the south of England soils the amount of potash is closely associated with that of alumina, being commonly about one-tenth; it is, therefore, about one-thirtieth of the clay. Some examples are given in Table XCIV.

The “available” potash² shows no kind of regularity, but varies between 5 and 50 per cent. of the quantity extracted by strong acids. In deciding whether or not sufficient is present, attention must be paid to the soil, the crop and the

¹For the effect of soil iron compounds on soluble phosphates see A. C. de Jongh, *Int. Mitt. Bodenkunde*, 1914, 4, 32-45.

²I.e. extracted by 1 per cent. citric acid.

TABLE XCIV.—POTASH AND CLAY CONTENTS OF VARIOUS SOILS.

| No. of Soil. | Percentage of Al_2O_3 . | Percentage of K_2O . | Ratio $\frac{\text{K}_2\text{O}}{\text{Al}_2\text{O}_3}$. | Percentage of Clay. | Ratio $\frac{\text{K}_2\text{O}}{\text{Clay}}$. |
|--------------|---|--------------------------------------|--|---------------------|--|
| 112 | 4'07 | '45 | '11 | 13'1 | '034 |
| 120 | 2'84 | '31 | '11 | 10'4 | '029 |
| 100 | 3'83 | '40 | '10 | 11'2 | '035 |
| 133 | 3'67 | '44 | '12 | 11'7 | '037 |
| 103 | 3'66 | '30 | '08 | 11'9 | '025 |
| 161 | 7'97 | 1'08 | '14 | 27'7 | '039 |
| 67 | 11'75 | 1'44 | '12 | 36'8 | '039 |
| 118 | 3'46 | '404 | '12 | 11'5 | '035 |
| 79 | 5'14 | '40 | '08 | 15'3 | '026 |
| 43 | 10'45 | '76 | '07 | 33'8 | '022 |
| 147 | 7'88 | '96 | '12 | 22'5 | '043 |

rainfall. Thin chalky soils, sandy soils, and soils rich in organic matter are peculiarly responsive to potassic manures, whilst clay soils generally are not. Carbohydrate-making crops, like sugar-beet, mangolds, and potatoes also invariably want more potash than they find in the soil or in dung. Potassic manures also tend to prolong the life of the plant, and, therefore, to increase the yield in dry districts where the conditions all tend to early stoppage of growth. Illustrations are afforded in Table XCV. where soils in dry districts, known to respond profitably to potassic manures, are compared with soils in places of much higher rainfall where potassic manures do not prove profitable.

TABLE XCV.—“AVAILABLE” POTASH IN SOILS OF KNOWN BEHAVIOUR TOWARDS POTASSIC MANURES.

| | Soils Responding to Potassic Manures. | | | | Soils not Responding to Potassic Manures. | | | |
|---|---------------------------------------|---------|----------|-----------|---|---------|----------|----------|
| | East Kent. | | Surrey. | Sussex. | West Sussex. | | | Kent. |
| | Newington. | Barton. | Redhill. | Patching. | Oving. | Rogate. | Stedham. | Yalding. |
| Available K_2O | '013 | '015 | '010 | '007 | '014 | '024 | '010 | '044 |
| K_2O extracted by conc. HCl | '200 | '404 | '181 | '260 | '43 | '18 | '14 | '59 |
| Clay | 6'0 | 11'5 | 7'8 | 25'5 | 15'9 | 6'7 | 5'5 | 9'1 |
| Rainfall | 22'5 | 23 | 27'7 | 28'6 | 28 | 33 | 33 | 24 |

All are arable soils. The chalk pastures on the South Downs usually contain less than '01 per cent. of available potash (*e.g.* the Patching soil), and they respond to potassic manures. It will be observed that '015 per cent. is insufficient in East Kent where the rainfall is 23 inches, whilst '010 per cent. suffices in West Sussex under 10 inches higher rainfall and generally better water-supply in the soil.

Phosphoric Acid.—Generally speaking, the largest amount of phosphoric acid is found in chalk soils, 0.2 to 0.25 per cent. being present; about 0.15 to 0.2 per cent. is found in good loams; sandy loams contain about 0.1 per cent. while poor clay pastures and poor sands contain still less. Little if any direct connection can be traced between the phosphoric acid and the productiveness; in general it tends to increase as the clay, fine silt, and silt increase—the poor clay pastures form a readily explained exception—but it does not appear to be closely associated with any one fraction like the potash. The amounts of “available” phosphoric acid vary enormously; Kentish hop gardens commonly contain from '05 to '18 per cent.; well-farmed arable soils contain some '015 per cent., while in poor worn-out pastures the quantity may sink as low as '002 per cent. In most cases these quantities are insufficient for some of the crops grown, especially where high quality or feeding value is aimed at; hop growers regularly, and, they maintain, profitably, apply phosphates to gardens already containing '05 per cent. of available phosphoric acid, whilst arable farmers use them for swedes when '015 per cent., or sometimes even more, is present. The exceptions to this rule are the light soils sufficiently provided with moisture and a forward climate; on these the need for phosphates appears to be less. But in all cases where much purchased food is fed on the land phosphates appear to be of advantage to the succeeding crop.

Rainfall does not appear to have so marked an effect in controlling the need for phosphates as it has for potassic manures. The explanation is to be found in the fact that phosphates are useful both in dry and in moist situations:

they tend to promote root development, an obvious advantage in a dry soil where the plant will fail unless the roots strike into the deeper, moister layers; they also stimulate the vital processes going on at the end of the season and are thus valuable in wet, cold districts. But rainfall and water-supply are important factors in determining the choice of phosphates on arable land; basic slag proves less useful than superphosphates on dry soils, but it is sometimes nearly as useful on moister soils or under higher rainfall. The amount of chalk in the soil is not the determining factor, but the moistness; if, as often happens, a chalky soil is dry, superphosphates will prove the more useful; where the soil is moister, basic slag is as good, and of course cheaper. Evidence is accumulating that mineral phosphates are often of value. On grass land basic slag is often more effective than superphosphate.

The Relative Advantages of Mechanical and Chemical Analysis.

The fundamental distinction between mechanical and chemical analysis is that the former deals with the whole of the soil, which it sorts out into fractions of varying sizes, while the latter deals only with the part that is readily dissolved by acids. Mechanical analysis, therefore, gives a picture of the whole (albeit very incomplete), while chemical analysis does not; it is in consequence eminently suited for the purpose of a soil survey, the chief object of which is to classify and describe the soils. Further, it enables the investigator to explain to some degree the observed water relationships of the soil when sufficient is known about the water-supply, and also to account for many of the peculiarities observed in cultivation. It enables him to say, as far as can be said on our present knowledge, whether any observed defects are due to defects in the soil or its situation, or to the system of management that has been adopted. As it cannot be interpreted fully without a knowledge of the amounts of organic matter and calcium carbonate present, these two quantities must be determined in every sample.

In the preceding discussion the soils have all belonged to one type—the much-weathered soils of the South of England. We have seen that in this case there is a close correlation between the potash, the alumina and the clay. For purposes of a survey it seems superfluous to determine these two bases in every sample taken. The iron oxide shows a general but by no means a close correlation with the others; but no connection could be traced between iron oxide and fertility in the soils examined by the author, the iron oxide being almost always less than 5 per cent. in amount. Nor did it appear that the ratio of lime to magnesia in these soils was significant. The nitrogen is closely correlated with the organic matter, *i.e.* the loss on ignition. The total phosphoric acid shows no great variations in the different soils, but the available phosphoric acid, like the available potash, varies greatly with the management of the soil. Thus the figures obtained by chemical analysis, apart from the loss on ignition and the calcium carbonate, fall into two groups: the nitrogen, potash and alumina, which are so closely correlated with quantities already determined in the mechanical analysis that their separate determination is almost superfluous; and the iron oxide, magnesia, lime, etc., which do not give sufficiently useful indications to be worth determining in every case. Since chemical analysis fails to describe the soil with sufficient completeness for agricultural purposes Hall and Russell recommend that for purposes of a survey a large number of soils should be submitted to mechanical analysis, including the determination of organic matter and of calcium carbonate, and then a carefully chosen representative set should be analysed chemically so as to characterise the type; these can further serve as standards with which farmers' samples can be compared by the citric acid method. They agree with Whitney that mechanical analysis should form the basis of the survey, because it alone takes account of those physical functions—the regulation of the water-supply and therefore of the temperature, of the air supply, ease of cultivation, etc.—that play so large a part in determining the value of a soil.

But, on the other hand, mechanical analysis is restricted in its application and breaks down altogether on chalk soils, acid humus or peat soils, and neutral humus soils, while it gives useful indications only on the mineral soils, *i.e.* sands, loams and clays. Agricultural soils belong so largely to this group that the method is really applicable in by far the great majority of cases.

Among the mineral soils the chemical grouping cuts across the mechanical classification. When the clays are separated out and subjected to hydrofluoric acid treatment or fusion with alkalis and then analysed, they are seen to fall into two or more types, as shown in Table XXIX. (p. 102). Further evidence of dissimilarity among the clays is obtained by a study of the results of the acid extraction of the soil; in general the alumina is about one-third of the clay in amount and the potash is roughly one-tenth of the alumina; in other cases, however, very different relationships obtain.

For the comparison or characterisation of types chemical analysis becomes of considerable importance. For this purpose Hissink (136) and von 'Sigmond (266*a*) have each emphasised the value of extraction by strong HCl, though they do not agree as to the interpretation of the results. Hissink claims to be able, by suitable modification of the analytical process, to differentiate van Bemmelen's three groups:—

- (1) "Complex A," the "weathered silicates" capable of absorption and exchange of bases.
- (2) "Complex B," the less active "kaolin silicates."¹
- (3) Inert "unweathered silicates" incapable of absorption and base exchange effects.

The advantages of such discrimination are manifest, but von 'Sigmond is not prepared to admit that it can be done. He considers, however, that strong hydrochloric acid has a practical value for describing soils. Other chemists do not altogether agree: E. A. Mitscherlich sees no advantage in the method² (see p. 234).

¹ For a discussion of these see R. Gans, *Int. Mitt. Bodenkunde*, 1913, 3, 546.

² *Ibid.*, 1914, 4, 327.

SOIL SURVEYS.

Soil surveys of the following counties have been published :—

ENGLAND.

BEDFORD.—

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In France the surveys have been made on a petrogeological basis as initiated by M. Risler in 1856. The work is particularly associated with the Station Agronomique de l'Aisne et Laon. Many of the maps are beautifully drawn: for an example see *Journ. Min. Ag.*, 1920, 27, 57. In the United States an extensive soil survey is organised by the Dept. of Agriculture and in many of the individual States by the Colleges or Agricultural Experiment Stations. For the soil map of Germany see *Int. Mitt. Bodenkunde*, 1917, 7, 1.

APPENDIX I.

THE METHODS OF SOIL ANALYSIS.

How to Take the Sample of Soil.—Owing to the variation in composition of the soil at different depths it is particularly necessary that the sample should always be taken to the same depth and with a tool making a clean vertical cut. Samples taken with a spade are of very doubtful value and do not justify any lengthy examination. A suitable tool consists of a steel tube 2 ins. in diameter and 12 ins. long, with a $\frac{3}{4}$ -in. slit cut lengthwise and all its edges sharpened fixed on to a vertical steel rod, bent at the end to a ring 2 ins. in diameter, through which passes a stout wooden handle (Fig. 31). A mark is made 9 ins. from the bottom so that the boring process can be stopped as soon as this depth is reached. On withdrawing the tool the core of soil is removed by a pointed iron rod. Five or six samples should be taken along lines crossing the field so as to get as representative a sample as possible; the whole bulk must then be sent to the laboratory. Samples should not be taken from freshly ploughed or recently manured land.

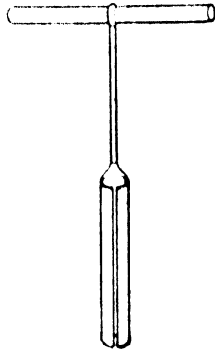


FIG. 31.—Tool for taking Soil Samples.

In very stony soils it is easier to use a 2-in. auger, but this does not, in our experience, yield as satisfactory a sample as the tool shown here.

A spud is useful for rapid preliminary inspection of waste land to ensure that the sample is normal; much disturbance of these soils is sometimes caused by rabbits.

For precautions to be taken in drawing the sample see Russell, *Journ. Bd. of Agric.*, 1916, **23**, 342, and for a discussion of the magnitude of the experimental error see Robinson and Lloyd, *Journ.*

Agric. Sci., 1915, 7, 144-153, and Leather, *Trans. Chem. Soc.*, 1902, 81, 883-886.

For American methods of sampling see *Bot. Gazette*, 1919, Feb., p. 173. C. B. Lipman and D. E. Martin¹ show that no further or unusual precautions need be taken when the sample is required for bacteriological purposes.

The Analysis.—On arrival at the laboratory the soil is spread out to dry, and is then pounded with a wooden pestle and passed through a 3 mm. sieve. The stones that do not pass through, and the fine earth that does, are separately weighed, and the proportion of stones to 100 of fine earth is calculated. Subsequent analytical operations are made on the fine earth.

Moisture.—Four or five grms. of the soil are dried at 100° C. till there is no further change in weight.

Organic Matter.—No accurate method of estimation has yet been devised. It is usual to ignite at low redness the sample dried as above. The loss includes organic matter, water not given off at 100° C., and carbon dioxide from the carbonates; allowance may be made for the latter, but not for the combined water. The carbon is sometimes determined either by the ordinary combustion or by some wet combustion method. Methods have also been described for determining "humus," but they have not come into general use. For ordinary purposes it is sufficient to take the loss on ignition as organic matter.

Total Nitrogen.—Kjeldahl's method is almost invariably adopted. About 25 to 30 grms. of soil are ground up finely in an iron mortar; 10 to 15 grms. are heated in a Kjeldahl flask with 20 to 25 c.c. of strong sulphuric acid for three-quarters of an hour; 5 grms. of potassium sulphate are added, and then a crystal of copper sulphate. The heating is continued till all the black colour has gone. Then cool and dilute the mixture, transfer the fluid part to a distillation flask, but leave as much as possible of the sand behind, wash well to remove all the adhering liquid. Add saturated soda solution till the liquid is strongly alkaline, distil, and collect the ammonia in standard acid.

Nitrates must be determined in a sample taken direct from the field and dried without any delay at 55° C.; 200 to 500 grms. of the dried soil are pressed firmly on to a Buchner funnel fitted to a filter flask, and distilled water is poured on. The first 300 c.c. of water

¹ *Soil Sci.*, 1918, 6, 131-36.

passing contains practically all the nitrates, but it is safer to wash more fully. The solution is poured into a flask covered by an inverted porcelain crucible-lid, 10 c.c. of 4 per cent. caustic soda and 1 or 2 c.c. of 3 per cent. potassium permanganate are added, and the whole is then boiled down to some 75 c.c. and kept just boiling for about two hours. If the permanganate is completely decolorised a little more is added until there is no appreciable change in half an hour. The excess is then destroyed by cautious addition of sodium sulphite solution and the solution is diluted to 200 c.c. and distilled down to 50 c.c. with the addition of 1 gram. powdered Devarda alloy, 10 c.c. more of 4 per cent. caustic soda and half a gram. of recently ignited lime. The condenser should be of pure tin with a short length of hard glass tubing at its lower end to dip into the N/50 sulphuric acid in the receiver. Shortly before the end of the distillation the cooling water is emptied out so that steam passes through. A large volume of hydrogen and spray is given off at the beginning of the operation, so special attention must be given to trapping. The titration is carried out as described under *Ammonia*.

In the United States the more rapid phenol sulphonic acid method is used. (See C. B. Lipman and L. T. Sharp, *Univ. Cal. Pub. Ag. Sci.*, 1912, **I**, 23-37.)

For statistical discussion of errors see D. D. Waynick, *Univ. Cal. Pub. Ag. Sci.*, 1918, **3**, 243-270.

Ammonia is determined by aeration. The apparatus consists of a glass tube sloping at an angle of about 40° ; its dimensions are about 83 cm. by 2.2 cm. and it has a pear-shaped bulb blown on it at about one-third of its length from the upper end, the small end of the bulb being downwards. It is closed at the lower end by a rubber stopper, through which a glass inlet tube for air passes close to the wall of the larger tube at the under side. The upper end of the large tube is connected by a rubber stopper with a short tube packed with cotton-wool to stop spray, and this in its turn is connected with an absorber containing from 5 to 10 c.c. of N/50 sulphuric acid diluted with water and a few drops of a 0.05 per cent. solution of methyl red. The freshly taken soil is passed as quickly as possible through a 3 mm. sieve, stones above this size being rejected; 25 grms. are placed at the lower end of the tube on a loose cotton-wool plug, and 50 c.c. of a solution containing 108 grms. of sodium carbonate crystals and 150 grms. of sodium chloride

per litre are added, together with a few drops of paraffin lamp-oil to stop foaming. The upper stopper is replaced and a current of purified air is sucked through the apparatus until the whole of the ammonia has been carried over into the absorber. With the amounts given a total of 1000 litres of air is sufficient; a good filter pump should aspirate this amount in from $3\frac{1}{2}$ to 4 hours. The current should not fall below 250 litres per hour. The acid is then poured into a hard glass flask, titrated with N/50 caustic soda till nearly neutral, boiled to expel carbon dioxide, cooled, and titrated to a clear yellow¹ (Fig. 32).

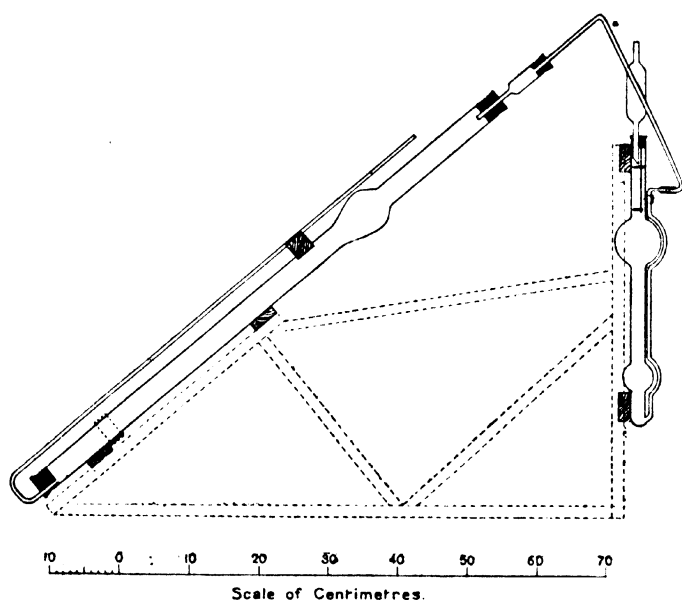


FIG. 32.

Carbonates are determined by treating a weighed quantity of the soil with dilute sulphuric acid and estimating the carbon dioxide evolved. Collins' calcimeter is a satisfactory instrument.²

Lime Requirement.—Hutchinson and McLennan's method for the determination of the lime requirement of the soil is as follows:

¹ See D. J. Matthews, *Journ. Agric. Sci.*, 1920, 10, 72.

² *Journ. Chem. Soc. Ind.*, 1906, 25, 518. The apparatus is made by Messrs. Brady and Martin, Newcastle-on-Tyne.

10 to 20 grms. of the soil are placed in a bottle of 500 to 1000 c.c. capacity, together with 200 to 300 c.c. of approximately N/50 solution of calcium bicarbonate, and the air in the bottle is displaced by a current of carbon dioxide in order to avoid possible precipitation of calcium carbonate during the period of the determination. The bottle is then placed in a shaking machine for three hours, after which time the solution is filtered and an aliquot portion of the filtrate is titrated against N/10 acid, using methyl orange as indicator. The difference in strength of this filtrate and that of the initial solution represents the amount of calcium carbonate absorbed, each cubic centimetre of N/10 acid being equal to 5 mgs. calcium carbonate.

For a criticism of the method see E. A. Fisher (99) and for a modification see F. W. Warth and M. P. Saw, *Chemical Mem. Dept. Ag. India*, 1919, 5, 157-172. For an account of the numerous other methods see H. R. Christensen (67*b*).

Hydrogen Ion Concentration, P_H value (see p. 115, and E. A. Fisher (99)).

Mineral Substances.—Complete analysis of a soil after the silicates have been decomposed and the silica volatilised by treatment with hydrofluoric acid is only rarely attempted. The British method, adopted by the Agricultural Education Association, is thus described by Hall: "20 grms. of the powdered soil are placed in a flask of Jena glass, covered with about 70 c.c. of strong hydrochloric acid, and boiled for a short time over a naked flame to bring it to constant strength. The acid will now contain about 20.2 per cent. of pure hydrogen chloride. The flask is loosely stoppered, placed on the water bath, and the contents allowed to digest for about forty-eight hours. The solution is then cooled, diluted, and filtered. The washed residue is dried and weighed as the material insoluble in acids. The solution is made up to 250 c.c., and aliquot portions are taken for the various determinations. The analytical operations are carried out in the usual manner, but special care must be taken to free the solution from silica or organic matter" (*The Soil*). As a rule only potash and phosphoric acid are determined, but where necessary other bases are estimated in the usual way.

Hissink¹ has discussed the value of strong HCl as a solvent in soil analysis. American methods are described by F. E. Bear and

¹*Internat. Mitt. Bodenkunde*, 1915, 5, 1-24. For determination of iron see Morison and Doyne, *Journ. Agric. Sci.*, 1914, 6, 97.

M. Salter,¹ and Continental methods by von 'Sigmund (2661). See also p. 344.

Potash.—50 to 100 c.c. of the solution are evaporated to dryness, after addition of 0.5 gm. of pure CaCO_3 if the original soil did not effervesce on addition of HCl . Two courses are then open:

(a) The residue is *gently* ignited over a Bunsen burner until completely charred, and is then extracted with water until all the potassium chloride has dissolved (Neubauer's method² (212)). To the clear filtrate 5 c.c. of platinum chloride (containing .005 gm. Pt per c.c.) are added and the mixture slowly concentrated on the water bath to a very small bulk. The potassium platino-chloride is filtered off in a Gooch crucible, washed with 80 per cent. alcohol, dried and weighed.

or (b) Add 10 c.c. of 5 per cent. baryta solution, evaporate to dryness, ignite and take up with water as in (a), add 2.5 c.c. perchloric acid (sp. gr. 1.12), concentrate until dense fumes are given off, allow to cool, add 20 c.c. 95 per cent. alcohol, and stir. Decant off the clear alcohol, add 40 c.c. alcohol containing 0.2 per cent. perchloric acid, transfer to a tared filter paper, wash with 50 to 100 c.c. of 95 per cent. alcohol till the runnings are no longer acid, dry at 100° and weigh as KClO_4 .

Phosphoric Acid.—The charred residue from which the potassium chloride has been removed is digested for half an hour on a sand bath with 50 c.c. of 10 per cent. H_2SO_4 and filtered; the filtrate is treated with 25 c.c. conc. NH_4NO_3 solution and warmed to 55°C .; 25 c.c. ammonium molybdate, previously warmed to 55°C ., is added and the whole allowed to stand for two hours and filtered. Wash with 2 per cent. NaNO_3 till the washings are neutral, transfer the precipitate and filter paper to the beaker used for the precipitation, and add a known volume of standard alkali so that the precipitate completely dissolves. Measure the excess by titration, using phenolphthalein as indicator. 1 c.c. of $\frac{\text{N}}{10}$ alkali = .0003004 gm. P_2O_5 .³

¹ West Virginia Bul., 159, 1916.

² The older method due to Tatlock is still sometimes used. It is described by Dyer (91).

³ This volumetric method was originally described in Bull. 46 (revised), United States Division of Chemistry (Washington, 1898). A careful examination has been made by Prescott and the conditions laid down under which it gives satisfactory results (Journ. Agric. Sci., 1914, 6, 111-120). Prescott's modification is given here. The method is applicable for the "available" P_2O_5 , but in

Available Potash and Phosphoric Acid.—Dyer's directions are as follows: 200 grms. dry soil are placed in a Winchester quart bottle with 2 litres of distilled water, in which are dissolved 20 grms. of pure citric acid. The soil is allowed to remain in contact with the solution at ordinary temperatures for seven days, and is shaken a number of times each day. The solution is then filtered, and 500 c.c. taken for each determination; this is evaporated to dryness, and gently incinerated at a low temperature. The residue is dissolved in hydrochloric acid, evaporated to dryness, redissolved, and filtered; in the filtrate the potash is determined. For the phosphoric acid determination the last solution is made, as before, with nitric acid.

Mechanical Analysis.—The object is to obtain information about the size of the ultimate particles of which the soil is composed; the compound particles are therefore broken down by treatment with hydrochloric acid, and afterwards with ammonia. Direct measurement of the ultimate particles is found to be impracticable; indirect methods have to be adopted, depending on the time taken to fall through a column of water of given height. When a body falls through a vacuum the time taken is independent of its size or weight, but if air or any other fluid is present the case becomes more complicated and the proper mathematical relationship has been found by Stokes to be $v = \frac{2ga^2(\sigma - \rho)}{9\eta}$, where v = velocity of the falling particle, σ its density, a its radius (assuming it to be a sphere), and ρ the density and η the coefficient of viscosity of the medium (*Trans. Camb. Phil. Soc.*, 1851, vol. ix., p. 8).

The numerical values at 16° C. are: $g = 981$, $\sigma = 2.5$, $\rho = 1$, $\eta = .011$, and the equation therefore reduces to $v = a^2 \times 29730$, or $a = \frac{\sqrt{v}}{172}$ cm.

The calculated and observed values are found to agree fairly well, differences being due to the fact that the particles are not true spheres, and to the existence of convection currents produced by changes of temperature. The effect of variations in temperature is discussed by Robinson in *Journ. Agric. Sci.*, 1914, 7, 142.

The method adopted by the Agricultural Education Association (see *Journ. Agric. Sci.*, 1906, i., 470) is as follows:—

this case the residue from the citric acid extraction has first to be heated two hours at 120° to 160° to render the silica insoluble. The older method is described by Dyer (91).

(1) Ten grms. of the air-dry earth, which has passed a 3 mm. sieve, are weighed out into a porcelain basin and triturated with 100 c.c. of N/5 hydrochloric acid, further acid being added if much calcium carbonate is present. After standing in contact with the acid for one hour, the mixture is transferred to a dried, tared filter which is washed until acid-free, dried and weighed. The loss represents hygroscopic moisture and material dissolved by the acid.

(2) The soil is washed off the filter with ammoniacal water on to a small sieve of 100 meshes to the linear inch, the portion passing through being collected in a beaker marked at 10, 8.5, and 7.5 cm. respectively from the bottom. The portion which remains upon the sieve is dried, weighed, and divided into "fine gravel" and "coarse sand" by means of a sieve with round holes of 1 mm. diameter. The portion which does not pass this sieve is the "fine gravel". This is dried and weighed. The difference gives the "coarse sand". If required, both these fractions can also be weighed after ignition.

(3) The portion which passed the 100 mesh sieve is triturated with a rubber pestle (made by inserting a glass rod as handle into an inverted rubber stopper), and the beaker filled up to the 8.5 cm. mark and allowed to stand for twenty-four hours. The ammoniacal liquid which contains the "clay" is then decanted off into a Winchester quart bottle, the operation being repeated as long as any matter remains in suspension for twenty-four hours. The liquid containing the "clay" is either evaporated in bulk or measured, and, after being well shaken, an aliquot portion taken and evaporated. In either case the dried residue consists of "clay" and "soluble humus". After ignition the residue gives the "clay," and the loss on ignition the "soluble humus". Here minimum value of $v = 0.00001$ cm. per second, and the minimum diameter of the particles = .0013 mm.

(4) The sediment from which the "clay" has been removed is triturated as before in the beaker, which is filled to the 10 cm. mark and allowed to stand for 100 seconds. The operation is repeated until the "fine sand" settled in 100 seconds is clean, when it is collected, dried, and weighed.

Here minimum value of $v = 0.1$ cm. per second; the calculated minimum diameter = .037 mm.

(5) The turbid liquid decanted from the "fine sand" is collected in a suitable bottle, allowed to settle, and the clear liquid syphoned or decanted off. The sediment is then washed into the marked

beaker and made up to the 7.5 cm. mark. After stirring, it is allowed to settle for twelve and a half minutes, and the liquid decanted off. The operation is then repeated as before till all the sediment sinks in twelve and a half minutes, leaving the liquid quite clear. The sediment obtained is the "silt," which is dried and weighed as usual. The liquid contains the "fine silt," which, when it has settled down, can be separated by decanting off the clear liquid, and dried and weighed.

For silt minimum value of $v = 0.01$ cm. per second, minimum diameter of particles = 0.012 mm. For fine silt the diameter obviously lies between this value and the one found for clay.

When it is desired to compare the results with American data the fine silt can be divided into two groups: settling for two hours five minutes brings out a group 0.01 to 0.005 mm. diameter, and the remainder lies between 0.005 and 0.002 mm. diameter. The fractions can then be made to correspond fairly closely with those adopted in the United States.

(6) Determinations are made of the "moisture" and "loss on ignition" of another 10 grms. of the air-dry earth. The sum of the weights of the fractions after ignition + loss on ignition + moisture + material dissolved in weak acid should approximate to 10 grms.

(7) It is advisable to make a control determination of the "fine gravel" in a portion of fifty grms. of the air-dry earth. The soil should be treated with acid, as in (1), and after that is removed by decantation may be at once treated with dilute ammonia and washed on the sieve with 1 mm. round holes. The "fine gravel" left on the sieve is then dried and weighed.

The American method is somewhat different. The breaking down of the aggregates is brought about by physical means—e.g. violent shaking—and sedimentation is hastened by a centrifugal apparatus which is a distinct improvement on the British method: the centrifuge was also used by Beam in Khartoum.¹ Hilgard does not adopt a sedimentation method but proceeds in the converse manner; he collects and weighs the particles carried off by successive streams of water of varying velocity. Full details are given in *Bull.* 24, *Bureau of Soils*, 1904, and in Wiley's *Agricultural Analysis*, vol. i., where the continental methods are also described. An entirely new method has been described by Odén (218c).

¹ W. Beam, *The Mechanical Analysis of Arid Soils* (*Cairo Scientific Journal*, 1911, 5, 107-119). Pub. Wellcome Tropical Research Lab., Khartoum.

Methods of Sand and Soil Cultures.—See Hellriegel (130*b*) and—
Sand, McCall, A. G., *Journ. Amer. Soc. Agron.*, 1915, **7**, 249-
282; *Soil Sci.*, 1916, **2**, 207-253; *Journ. Amer. Soc. Agron.*, 1918,
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Ag. Res., 1919, **18**, 11.

Amounts of Various Substances Absorbed from the Soil by the Common Agricultural Crops of England. (Watlington.) *

| | Weight of Crop. | | Total Pure Ash. | Nitrogen. | Sulphur. | Potash. | Soda. | Lime. | Magnesia. | Phos- phoric Acid. | Chlorine. | Silica. |
|--------------------------|-----------------|-------|-----------------|-----------|----------|---------|-------|-------|-----------|--------------------------|-----------|---------|
| | At Harvest. | Dry. | | | | | | | | | | |
| Wheat, grain, 30 bush. | lb. | lb. | lb. | lb. | lb. | lb. | lb. | lb. | lb. | lb. | lb. | lb. |
| " straw . . . | 1,800 | 1,530 | 30 | 34 | 27 | 93 | 0.6 | 1.0 | 3.6 | 14.2 | 0.1 | 0.6 |
| Total crop . . . | 3,158 | 2,653 | 142 | 16 | 5.1 | 19.5 | 2.0 | 8.2 | 3.5 | 6.9 | 2.4 | 96.3 |
| Barley, grain, 40 bush. | 4,958 | 4,183 | 172 | 50 | 7.8 | 28.8 | 2.6 | 9.2 | 7.1 | 21.1 | 2.5 | 96.9 |
| " straw . . . | 2,080 | 1,747 | 46 | 35 | 2.9 | 9.8 | 1.1 | 1.2 | 4.0 | 16.0 | 0.5 | 11.8 |
| Total crop . . . | 2,447 | 2,080 | 111 | 14 | 3.2 | 25.9 | 3.9 | 8.0 | 2.9 | 4.7 | 3.6 | 56.8 |
| Oats, grain, 45 bush. | 4,527 | 3,827 | 157 | 49 | 6.1 | 35.7 | 5.0 | 9.2 | 6.9 | 20.7 | 4.1 | 68.6 |
| " straw . . . | 1,890 | 1,625 | 51 | 34 | 3.2 | 9.1 | 0.8 | 1.8 | 3.6 | 13.0 | 0.5 | 19.9 |
| Total crop . . . | 2,835 | 2,353 | 140 | 18 | 4.8 | 37.0 | 4.6 | 9.8 | 5.1 | 6.4 | 6.1 | 65.4 |
| Meadow Hay, 1½ tons. | 4,725 | 3,078 | 191 | 52 | 8.0 | 46.1 | 5.4 | 11.6 | 8.7 | 19.4 | 6.6 | 85.3 |
| Red Clover Hay, 2 tons | 3,360 | 2,822 | 203 | 49 | 5.7 | 50.9 | 9.2 | 32.1 | 14.4 | 12.3 | 14.6 | 56.9 |
| Beans, grain, 30 bush. | 4,480 | 3,763 | 258 | 98 | 0.4 | 83.4 | 5.1 | 90.1 | 28.2 | 24.9 | 9.8 | 7.0 |
| " straw . . . | 1,920 | 1,613 | 58 | 78 | 4.4 | 24.3 | 0.6 | 2.9 | 4.2 | 22.8 | 1.1 | 0.4 |
| Total crop . . . | 2,340 | 1,848 | 99 | 29 | 4.9 | 42.8 | 1.7 | 26.3 | 5.7 | 6.3 | 4.3 | 6.9 |
| Turnips, roots, 17 tons. | 4,160 | 3,461 | 157 | 107 | 0.3 | 67.1 | 2.3 | 20.2 | 0.9 | 29.1 | 5.4 | 7.3 |
| " leaf . . . | 38,080 | 3,126 | 218 | 61 | 15.2 | 108.6 | 17.0 | 25.5 | 5.7 | 22.4 | 10.9 | 2.6 |
| Total crop . . . | 11,144 | 1,531 | 146 | 40 | 5.7 | 40.2 | 7.5 | 48.5 | 3.8 | 10.7 | 11.2 | 5.1 |
| Swedes, roots, 14 tons. | 40,504 | 4,657 | 364 | 110 | 20.9 | 148.8 | 24.5 | 74.0 | 9.5 | 33.1 | 22.1 | 7.7 |
| " leaf . . . | 31,360 | 3,349 | 163 | 70 | 14.6 | 63.3 | 22.8 | 19.7 | 6.8 | 16.0 | 6.8 | 3.1 |
| Total crop . . . | 4,704 | 706 | 75 | 28 | 3.2 | 16.4 | 9.2 | 22.7 | 2.4 | 4.8 | 8.3 | 3.6 |
| Mangolds, roots, 22 tons | 46,064 | 4,053 | 238 | 68 | 17.8 | 79.7 | 32.0 | 42.4 | 9.2 | 21.7 | 15.1 | 6.7 |
| " leaf . . . | 49,280 | 5,914 | 426 | 98 | 4.9 | 222.8 | 69.4 | 15.9 | 18.3 | 36.4 | 42.5 | 8.7 |
| Total crop . . . | 18,233 | 1,654 | 254 | 51 | 9.1 | 77.9 | 49.3 | 27.0 | 24.2 | 16.5 | 40.6 | 9.2 |
| Potatoes, tubers, 6 tons | 67,513 | 7,568 | 680 | 140 | 14.0 | 300.7 | 118.7 | 42.0 | 42.5 | 52.9 | 84.1 | 17.4 |
| | 13,140 | 3,360 | 127 | 46 | 2.7 | 76.5 | 3.8 | 3.4 | 6.3 | 21.5 | 4.4 | 2.6 |

* The yields quoted are not averages though they are commonly obtained on farms.

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AUTHOR INDEX.

The numbers in square brackets marked B refer to numbers in the bibliography to which the reader should turn for fuller reference.

- ABBE, Cleveland, [B 1].
 Abbott, J. B., 112.
 Acqua, C., 90.
 Adametz, L., 256.
 Adeney, W. E. [B 2], 190, 194, 214.
 Ageton, C. N. [B 105], 304.
 Aiyer, S. [B 126], 213, 256, 300.
 Albrecht, W. A., 207.
 Ali, Barkat, 274.
 Allen, E. R., 199, 262.
 Allison, F. E. [B 60], 169, 213, 273, 290.
 Alves, A. [B 151b], 201.
 Alway, F. J. [B 3], 137, 221, 223, 226.
 Ames, J. W. [B 4], 119, 211.
 Amos, A., 84, 157.
 André, G. [B 30, 31], 138, 146, 152, 297.
 Appleyard, A. [B 241g], 227, 228, 275, 276, 297.
 Ardern, E., 212.
 Aristotle, 152.
 Armsby, H. P., 156.
 Armstrong, E. F. [B 5], 87, 215.
 — H. E. [B 5], 87, 236.
 Arnd, Th. [B 6, 278], 210, 307.
 Ashby, S. F. [B 7], 188, 203, 261, 262, 318, 331.
 Ashley, H. E., 170.
 Aso, K. [B 277].
 Atkins, W. R. G., 2 2.
 Atterberg, A., 98.
 BACH, N., 161.
 Bacon, Francis, [B 8], 2.
 Bahr, F. [B 93], 113, 143.
 Bailey, C. H., 44.
 Baker, T. T., 90.
 Bancroft, W. D., 148.
 Barger, G., 195.
 Barlow, B. [B 125], 206, 208.
 Barnes, J. H., 274.
 Bassett, H., 120.
 Bauer, H. [B 233c], 124.
 Baule, B. [B 6], 34.
 Baumann, A. [B 10], 111, 130, 140.
 Beam, W., 355.
 Bear, F. E. [B 11], 243, 273, 351.
 Beckley, V. A. [B 12], 141, 142.
 Bedford, Duke of, [B 25].
 Beijerinck, Martinus W. [B 13-18], 26, 143, 199, 202, 204, 208, 260.
 Bell, J. M. [B 65d].
 Bemmelen, Jakob M. van, [B 19 25], 27, 101, 105, 130, 140, 148, 155, 344.
 Benz, Max, [B 310].
 Bergu, G., 234.
 Berman, N., 186.
 Berry, R. A. [B 320], 234.
 Berthelot, Marcellin, [B 26-33], 25, 26, 138, 195.
 Bertholon, Abbé, [B 34], 87.
 Bertrand, Gabriel, [B 35], 76.
 Berzelius, J. J., 12.
 Bewley, W. F. [B 36], 72, 204.
 Bialobloki, J. [B 47], 35.
 Bierema, S. [B 38], 210.
 Birner, H. [B 39].
 Bizzell, James A. [B 183], 243, 298, 299.
 Blackman, F. F. [B 40], 28, 35, 38.
 — V. H., 28, 88, 91.
 Blanck E. [B 170, 224c f], 34, 45, 101, 201, 210, 233, 234, 305.
 Blair, A. W., 181, 186, 243.
 Bocker, F., 152.
 Boedecker, C., 155.
 Boerhaave, H. [B 41], 5.
 Bogdanow, S., 77, 234.
 Bolley, H. L., 282, 295.
 Bonazzi, A., 188.
 Bottomley, W. B. [B 4 e], 236, 249.
 Bouilhac, R. [B 43, 44], 209, 256.
 Boussingault, J. B. [B 45-48, 88], 12, 15, 20, 175, 178, 194, 227.

- Bouyoucos, G. J. [B 49], 125, 173, 225, 233.
 Boyle, Robert, [B 50], 3, 4.
 Breazeale, J. F. [B 51, 65a, 179], 73, 79, 139, 152, 236, 238, 248.
 Bredemann, G. [B 52], 200.
 Bredig, G., 215.
 Brechley, Winifred E. [B 53, 121d], 51, 52, 76, 78, 83, 84, 85, 91, 173, 237, 238, 241, 249, 306.
 Bretschneider, P. [B 54], 21.
 Brierley, W. B., 257.
 Brigham, R. O., 58.
 Briggs, L. J. [B 55], 43, 47, 125, 144, 152, 221, 224, 226.
 Bristol, B. Muriel, [B 56], 254.
 Broounoff, P. [B 57].
 Brown, C. E., 211.
 — Adrian J. [B 58], 87.
 — Horace, T. [B 59], 38, 57.
 — Percy E. [B 60, 176], 211, 213, 262, 263, 265, 269, 273, 275, 279.
 Brunchorst, J., 25.
 Brustlein, F., 156.
 Buddin, Walter, [B 61], 169, 266, 295.
 Buisson, J. P. du, 282.
 Burd, John S. [B 62], 234, 238, 296, 300, 334.
 Burgess, P. S. [B 63], 262, 263, 265, 273, 274.
 Burmeister, H., 249.
 Burri, R., 204.
 Butler, E. J., 256.
 Butt, N. I. [B 123], 49.
 CAILLETET, L. [B 64], 15.
 Caldwell, J. S., 221.
 Cameron, Frank K. [B 65, 145, 305], 27, 78, 110, 122, 124, 139, 156, 173, 174, 233, 238, 247.
 Campbell, F. H., 156.
 Candolle, A. de, 244.
 Cannon, W. A., 53.
 Caron, A., 27.
 Carter, E. G. [B 113 c, d], 272, 273, 275.
 Cauda, A., 289.
 Chauzit, B., 304.
 Chick, Harlette, [B 66], 190.
 Christensen, Harald R. [B 67], 114, 118, 204, 242, 243, 351.
 Christie, A. W., 125.
 Clark, E. D., 282.
 Clausmann, P. [B 102], 76.
 Clayton, J. [B 140f], 177, 273.
 Clevenger, C. B., 81.
 Cobbett, William, 6.
 Coleman, D. A. [B 152], 200, 250, 275, 290.
 Coleman, Leslie C. [B 68], 189, 190.
 Collins, S. H., 350.
 Colville, F. V., 244.
 Comber, N. [B 69], 162.
 Conn, H. J. [B 70], 187, 216, 260, 271.
 Conner, S. D., 112.
 Cook, R. C., 78, 265.
 Coville, F. V., 240.
 Coudon, H. [B 207b], 185.
 Cowie, G. A., 215.
 Crescentius, Petrus, 1.
 Crowther, Charles, [B 71], 82, 268.
 Crump, L. M. [B 73c], 270, 290, 291.
 — W. B. [B 72], 222.
 Cunningham, A., 293.
 — Mary, 138.
 Curtis, R. E. [B 292e], 260.
 Cutler, D. W. [B 73], 270, 290, 291.
 Czapek, F., 233, 259.
 Czermak, W., 282.
 DACHNOWSKI, A., 260.
 Daikuhara, G. [B 74], 112, 210.
 Dakin, H. D., 185.
 Dale, E. [B 75], 257.
 Damon, S. C. [B 128b], 240.
 Darbishire, F. V. [B 241b], 84, 282, 281.
 Darwin, C. [B 76], 136.
 — Erasmus, [B 77], 8.
 — Francis, 54.
 Daubeny, C. G. B. [B 78], 234, 244.
 Davenport, A., 204.
 Davis, W. A. [B 78a], 68.
 — A. R., 208, 259.
 Davy, Humphry, [B 79], 11.
 Dawson, Maria, [B 80], 205.
 Deatrick, E. P., 76.
 Déhérain, P. P. [B 81], 209, 299.
 Delage, A. [B 82], 100.
 Delden, A. van, [B 15].
 Demoussy, E. [B 83], 57, 74, 79.
 Denison, W., 192.
 Densch, A. [B 278c].
 Detmer, W. [B 84], 129.
 Dixon, H. H., 89, 222.
 Dobson, Mildred E., 138, 139.
 Dokoutchoew, W. [B 85], 303, 310.
 Dorée, Chas., 138.
 Doryland, C. J. T. [B 86, 148], 186, 203, 211, 276.
 Doyme, H. C., 351.
 Drechsler, Chas., 260.
 Drouin, R., 256.
 Duchacek, F., 211.
 Duclaux, E. [B 87], 37.
 Dudgeon, E. C., 88.
 Duggar, B. M., 208, 259.
 Dumas, J. B. A., [B 88], 14, 20.
 Dumont, J. [B 89], 120, 275.

- Duncan, J. L., 308.
 Dundonald, Earl of, [B 90], 7.
 Dupetit, G. [B 103], 209.
 Dutton, F. V., 338.
 Dyer, Bernard, [B 91], 352.
 Dymond, T. S. [B 92], 77.

 EBBELS, W. P., 202.
 Edwards, C. S., 314.
 Ehrenberg, P. [B 93], 83, 113, 143, 259, 262.
 Ehrlich, F., 185.
 Einecke, A., 234.
 Elgee, F., 135.
 Eller, W., 143.
 Emeis, C., 104.
 Endell, K., 170.
 Engberding, D. [B 94], 276.
 Engels, O. [B 95], 234.
 Erdmann, E., 152.
 - R. [B 215a], 69.
 Eriksson, 25.
 Erlwein, [B 104], 88.
 Ernest, Adolf [B 273a, 274-5], 177, 197, 198, 199, 209, 269.
 Escombe, F. [B 59], 57.
 Esmarch, F., 254.
 Evelyn, J. [B 96], 7.

 FAHRF, G., 84.
 Fabricius, O. [B 97b], 269.
 Fahrenholtz, F. [B 257c].
 Failyer, G. H. [B 97], 100, 157.
 Farrow, E., 55.
 Fehrs, 293.
 Feilitzen, H. von, [B 97a], 269, 308.
 Felber, P., 213.
 Fellers, C. R., 290.
 Fischer, Hugo, [B 98, 170], 204, 210, 243.
 Fisher, E. A. [B 99], 113, 119, 351.
 Flügel, M., 34.
 Forbes, A. C., 135.
 Foreman, F. W., 345.
 Fowler, G. J., 212, 214.
 - L. W., 205.
 Frank, B. [B 100], 254, 255, 281.
 Franke, E. [B 224], 282.
 Frankland, E., 192.
 Franklin, T. B., 232.
 Fraps, G. S. [B 313], 262.
 Fred, E. B., 204, 274.
 Free, E. E. [B 100a, 178c], 51, 52, 53.
 Fresenius, L., 234.
 Freundlich, H., 162.
 Friske, K. [B 224e], 45.
 Fritsch, F. E., 255.
 Fröhlich, Otto, 34.

 Fry, W. H. [B 263], 121.
 Fuchs, F., 138.
 Fulmer, H. L., 273.
 Funchess, M. J., 212.

 GAGGER, C. S., 90.
 Gainey, P. L., 185, 188, 204, 202, 263.
 Gans, R. [B 101], 110, 344.
 Gaudechon, H. [B 208f], 279.
 Gaunersdorfer, J., 73.
 Gautier, A. [B 102], 76, 256.
 Gayon, U. [B 103], 209.
 Gedroiz, K., 104, 169.
 Georges, R. [B 257c], 38.
 Gericke, W. F. [B 175], 77.
 Gerlach, M. [B 104], 88, 180.
 Giglioli, L., 213.
 Gilbert, J. H. [B 161-166], 17, 20, 25, 54, 151, 180, 192.
 Gilchrist, D. A., 345.
 Gile, P. L. [B 105], 304.
 Gillespie, L. J. [B 105a], 114, 116, 176, 243.
 Giltner, W., 169.
 Gimmingham, C. T. [B 106, 120e], 132, 156, 242, 317.
 Girard, Aimé, 281.
 Giustiniani, E. [B 44], 256.
 Given, G. P., 262.
 Glauber, Johann Rudolph, [B 107], 3, 4.
 Gilinka, K. [B 107a].
 Godlewski, 189.
 Gola, G. [B 108], 123, 237, 239.
 Goheen, J. M., 205.
 Golding, John, [B 109, 241d], 204, 206, 287.
 Goldthorpe, H. C. [B 113c], 275.
 Goodey, T. [B 110], 289, 293, 294.
 Goodwin, W., 345.
 Gossel, F., 75.
 Gortner, R. A., 142.
 Gottheil, O. [B 111], 217.
 Götze, C. [B 224a], 193.
 Grafe, V., 79.
 Graham, Thomas, 148.
 Grandeau, M. L. [B 112], 15, 88, 143.
 Greaves, J. E. [B 113], 50, 84, 86, 146, 272, 273, 274, 275.
 Green, H. H. [B 181g], 84, 318.
 Greig Smith, R. [B 114], 249, 282.
 Grégoire, A., 336.
 Griffith, J. J., 83, 345.
 Groves, J. F., 54.
 Gully, E. [B 10, 116], 111, 130, 136, 139, 307.
 Gupta, N. Sen, 212.
 Gustafson, A. F., 107.
 Guthrie, F. B. [B 117], 86.

- HAAS, A. R. C., 81.
 Hagem, O. [B 118], 256.
 Hales, Stephen, [B 119], 5.
 Halket, A. C., 72.
 Hall, A. D. [B 120, 121], 45, 51, 52, 65, 77, 102, 116, 156, 157, 161, 164, 173, 183, 234, 238, 242, 296, 317, 327, 343, 345.
 Hanley, J. A., 155, 170, 351.
 Hannig, E., 222.
 Hansteen, B., 78.
 Hardy, W. B. [B 122], 161.
 Harris, F. S. [B 123], 49.
 — J. E. [B 124], 111.
 Harrison, F. C. [B 125], 206, 208.
 — J. B., 202.
 — W. H. [B 126], 213, 256, 300.
 Hart, F. B. [B 127], 76, 274.
 Harter, L. L. [B 145*b*].
 Hartwell, B. L. [B 128], 112, 212, 240.
 Hasenbäumer, J., 170.
 Hassler, C., 170.
 Hatschek, Emil, 148.
 Hazen, W. [B 263], 121.
 Heiden, E., 152.
 Heinrich, R. [B 129], 221.
 Heinze, B., 269.
 Hellriegel, H. [B 130], 24, 31, 43, 48, 59, 66, 70, 73, 196, 204, 356.
 Helmont, Johann Baptista Van, [B 131], 2, 4, 9.
 Helms, R. [B 117], 86.
 Hendrick, J. [B 132], 100, 102, 118, 334, 336, 346.
 Henneberg, W., 155.
 Henslow, J. S., 321.
 Herdman, W. A., 279.
 Hildebrandt, F. M., 157.
 Hilditch, T. P., 215.
 Hilgard, E. W. [B 133], 139, 143, 152, 223, 303.
 Hill, C. F., 345.
 Hills, T. L. [B 134], 199.
 Hiltner, L. [B 135, 215*b*], 205, 208, 276, 281, 305.
 Hirst, C. T. [B 113*b*], 44, 50, 86, 272.
 Hissink, D. J. [B 130], 344, 351.
 Hoagland, D. R. [B 136*a*, 260], 80, 81, 116, 118, 125, 127, 238, 356.
 Hoffman, C., 212.
 Home, Francis, [B 137], 6, 9, 22.
 Hopkins, C. G. [B 138], 191, 321.
 Hoppe-Seyler, F., 140.
 Houston, D., 281.
 Howard, A. [B 139], 50, 52, 229.
 — G. L. C. [B 139], 50, 52.
 Hudig, J., 294.
 Hughes, F. [B 92], 77.
 Huntemüller, Otto, 293.
 Hurst, L. A. [B 105*b*], 243.
 Hutchinson, H. B. [B 140, 241*c*], 17, 58, 119, 177, 191, 202, 204, 210, 213, 217, 241, 243, 249, 263, 266, 272, 273, 282 *et seq.*, 295, 350.
 IKEDA, K., 215.
 Iljin, V. [B 141], 46.
 Imaseki, T. [B 74], 210.
 Immendorff, H. [B 141], 193, 195.
 Ingen-Housz, Jan, [B 142], 9.
 Ingle, H., 318.
 Irvine, J. C., 138, 139.
 Itscherekov, B., 123.
 JAVILLIER, M. [B 143], 83.
 Jensen, C. A. [B 144, 179], 144, 248, 279.
 Jewson, S. T., 257.
 Jodidi, S. L., 146.
 Joffe, J. S., 81.
 Johnson, H. W. [B 60*c*], 211.
 Johnston, E. S., 157.
 Joly, J., 89.
 Jones, H. M., 186.
 Jongh, A. C. de, 339.
 Jorgensen, I. [B 231, 272], 51, 88.
 Joshi, N. V., 300.
 Jupe, C. W. C. [B 92], 77.
 KALMANN, W., 152.
 Kappen, H. [B 170], 81, 113, 210, 211, 233.
 Kaserer, H., 144, 213.
 Kearney, Thomas H. [B 145], 43, 78.
 Keen, B. A. [B 146], 167, 173, 221, 224, 226, 230, 232.
 Kellerman, K. F., 262.
 Kellermann, C. [B 234].
 Kelley, W. P., 191, 210, 263, 274.
 Kellner, O., 155.
 Kellogg, E. H. [B 60*b*], 211.
 Kreutzhage, C. [B 315], 77.
 Kidd, F. [B 147], 85.
 Kilroe, J. R., 346.
 King, F. H. [B 147*a*], 27, 173.
 — Walter E. [B 148], 276.
 Kirwan, Richard [B 149], 7, 8.
 Kliger, I. J., 186.
 Klimmer, M., 205.
 Knop, W. [B 150], 19, 76, 154, 157.
 Knudson, L., 57.
 Koch, Alfred, [B 151], 200, 201, 202, 203, 211, 281.
 — G. P., 274, 290.
 — Käte, 143.
 König, Alfred, [B 153], 153.
 — J., 170.

- Koning, C. J. [B 221], 257.
 Kopeloff, N. [B 152], 243, 250, 290.
 Kossowitsch, P. [B 154], 200, 255, 310.
 Kraus, Gregor, [B 155], 305.
 Krüger, R., 205.
 — W. [B 156], 58, 73, 282
 Krull, F. [B 151b], 201.
 Krzemieniewski, S. [B 157], 199, 261.
 Kullenberg, O., 155.
 Kübel, 3.

 LACHMANN, J. [B 158], 21, 25.
 Lafar, F., 189.
 Lagatu, H. [B 82], 100.
 Lainé, E. [B 208], 190, 194.
 Lampadius, 8.
 Langworthy, H. V., 169.
 Larsen, O. H. [B 67a].
 Lathrop, Albert C. [B 251], 248, 282.
 Lau, Erich [B 159], 227.
 Laurent, Emil, [B 160, 247], 26, 255.
 — J., 15.
 Lawes, J. B. [B 161-166], 17-20, 25, 54, 64, 151, 180, 192.
 Leather, J. W. [B 167], 221, 228, 239, 279, 299, 348.
 Lebedeff, A. J. [B 168], 208.
 Lechatelier, H. L., 100.
 Le Clerc, J. A., 79, 297, 300.
 Leeden, R. van der, 170.
 Lefèvre, Jules, [B 64, 169], 15.
 Lehenbauer, P. A., 54.
 Leitch, I., 54.
 Lemmermann, O. [B 170], 75, 210, 234.
 Lemström, S. [B 171], 88.
 Lendner, A., 256.
 Leoncini, G. [B 172], 105, 161.
 Lepeschkin, W. W., 54.
 Lesage, Pierre, [B 173], 88.
 Letts, E. A., 193.
 Lewin, K. R. [B 191], 289, 295.
 Lewis, F. J., 135.
 — W. C. McC., 161.
 Léwy, [B 48], 227.
 Liebig, Justus von, [B 174], 14-20, 22, 28, 154.
 Liechti, P., 212.
 Linder, S. E., 162.
 Linhart, G. A., 199.
 Lint, H. C. [B 152], 250, 290.
 Lipman, C. B. [B 175], 77, 125, 139, 200, 205, 262, 273, 274, 348, 349.
 — J. G. [B 176, 177], 186, 187, 212, 244, 263, 273, 275.
 Lippmann, E. O. von, 152.
 Litzendorff, J. [B 151b], 201.
 Livingstone, Burton Edward [B 178-9], 52, 54, 248.
 Livingstone, Grace J., 54.
 Lloyd, W. E., 347.
 Lockett, W. T., 212.
 Lodge, Oliver, 88.
 Loew, Oscar, [B 180], 67, 75, 76, 86, 216, 294.
 Löhnis, F. [B 181], 21, 190, 197, 198, 203, 215, 261, 263, 279.
 Lucanus, Benno, [B 39, 182].
 Luxmore, C. M., 345.
 Lynde, C. J., 105.
 Lyon, T. Lyttleton, [B 183], 118, 243, 298, 299.

 MAASSSEN, Albert, [B 184], 209.
 McBeth, I. G. [B 185], 177, 258, 300.
 McCall, A. G., 157, 350.
 — J. R., 125.
 McCaughey, W. G. [B 186], 100.
 McClendon, J. F., 114.
 McCool, M. M. [B 196].
 McDole, G. R. [B 30], 221.
 McGowan, W., 281.
 McHague, J. S. [B 187], 74.
 McIlvaine, T. C. [B 244], 81.
 McLane, J. W., 13, 144.
 McLean, H. C. [B 188], 181, 212, 213, 250.
 McLennan, K. [B 190], 119, 241, 295, 350.
 Maercker, M., 201.
 Maillard, L. C. [B 189], 142, 146.
 Manns, T. F., 205.
 Maquenne, L. [B 81a], 74, 79, 299.
 Marchal, Emile [B 190], 185, 187.
 Markham, Gervase, 311.
 Martin, C. H. [B 191], 289, 295.
 — D. E., 348.
 — J. C., 125.
 Marz, S. [B 243], 124.
 Maschaupt, J. G. [B 192], 296.
 Mason, J., 184.
 Masoni, G. [B 172], 105, 213.
 Massart, J., 306.
 Massey, A. B., 212.
 Matisse, G., 54.
 Matthaei, Gabrielle L. C. [B 193], 35 (now Howard, G. L. C., which see).
 Matthews, D. J., 350.
 Mayer, Ad. [B 194], 139, 140, 164.
 Mayow, John, [B 195], 3, 4.
 Maximow, N. A., 54.
 Mawley, A. E., 232.
 Mazé, P. [B 196], 7, 56, 58, 76, 80, 85, 236, 394.
 Meacham, M. R., 81.
 Mellish, H., 232.
 Merkle, F. G., 176.
 Meusel, E. [B 198], 209.

- Michelet, E. [B 199], 136.
 Miklauz, Rudolf, 140.
 Miller, H. G., 77.
 — N. H. J. [B 120b, 140, 200], 58, 129, 179, 242, 296.
 Minkman, D. C. J. [B 18].
 Mirasol, J. J., 113.
 Mitscherlich, E. A. [B 201], 28, 31, 64, 170, 234, 344.
 Miyake, K. [B 202], 28, 157, 185, 188.
 Mockeridge, F. A., 198, 236.
 Molisch, H., 88, 90.
 Molz, Emil, 304.
 Moore, B., 200, 255.
 — G. T., 290.
 Mooser, W., 212.
 Morgan, J. F. [B 203], 123.
 Morison, C. G. T. [B 120c, 204], 77, 161, 164, 165, 351.
 Morrow, C. A., 147.
 Morton, Chalmers, 192.
 Mosier, J. G., 107.
 Moss, C. E., 131.
 Mosséri, V., 100.
 Mulder, C. J. [B 205], 129, 138.
 Muller, P. E. [B 206], 136.
 — P. Th., 293.
 Müntz, M., 164, 165.
 Münster, F., 235.
 Muntz, A. [B 207, 208, 245], 23, 185, 190, 194, 195, 279.
 Murray, T. J. [B 209].
- NAGAOKA, M. [B 210, 211], 76, 210.
 Nakano, H., 255.
 Nazarova, P. [B 141], 46.
 Neller, J. R. [B 3d], 137, 185.
 Neubauer, Hugo, [B 212], 352.
 Neumann, P. [B 213], 206.
 Newman, J. E., 88.
 — L. F., 345.
 Nilson, Lars Fredrik, 234.
 Nobbe, F. [B 215], 69, 205, 208.
 Nolte, O. [B 216], 122.
- OBERLIN, [B 217], 280.
 Odén, Sven, [B 218], 95, 113, 119, 130, 140, 141, 143, 162, 355.
 Oehler, R., 289.
 Ogg, W. G. [B 132], 100, 102, 118, 334, 336, 346.
 Olaru, D., 207.
 Oliver, F. W., 314.
 Omelianski, W. [B 219, 311b], 177, 185, 189, 190, 191, 261.
 Osterhout, W. J. V. [B 220], 78.
 Ostrovskaja, M. [B 141], 46.
 Ostwald, Wo., 148, 161.
- Oudemanns, A. C. [B 221], 257.
 Owen, Irving L. [B 177], 273.
- PALISSY, Bernard, [B 222], 1.
 Paine, S. G., 72.
 Parker, F. W., 74.
 Parkinson, S. T., 89.
 Parr, A. E. [B 181b], 263.
 Pasteur, Louis, 23.
 Patten, A. J., 211.
 — H. E. [B 65c], 156, 157.
 Paturel, G., 67.
 Peck, S. S., 202, 273.
 Pember, F. R. [B 128a, 179], 112, 212, 248.
 Perciabosco, F., 59.
 Petersen, J. B., 254.
 Peterson, W. H. [B 127, 223], 76.
 Petherbridge, F. R. [B 241e], 146, 246, 248, 287, 295.
 Pettenkofer, M. v., 228.
 Pfeiffer, Th. [B 224], 34, 45, 193, 201, 233, 234, 282, 305.
 Pickering, S. U. [B 225], 162, 169, 246, 282.
 Picton, H., 162.
 Piemeisel, R. L., 43.
 Pillai, N. K. [B 181d], 198.
 Pitra, J., 211.
 Pitz, W., 77.
 Plymen, F. J. [B 120a], 234.
 Portheim, L. R. v., 79.
 Potter, R. S., 120, 147.
 Pratt, O. A., 257.
 Prázmowski, Adam, [B 227].
 Prescott, J. A. [B 228, 241h], 150, 157, 275, 294, 299, 352.
 Prianischnikow, D. [B 229], 58, 155.
 Priestley, Joseph [B 230], 8, 20.
 — J. H. [B 231], 88.
 Pringsheim, E., 256.
 — Hans, [B 232], 202.
 Pugh, E. [B 164], 20, 192.
 Purvis, O. N., 69.
 Pusey, P., 17.
- QUENSELL, E., 211.
- RAHN, Otto, 215.
 Ramann, E. [B 233], 98, 113, 124, 135, 155, 164, 165, 234, 258, 259.
 Rambaut, A. A., 232.
 Rathmann, W. [B 224], 234.
 Raumer, E. von [B 234], 74.
 Rayner, M. C., 254, 306.
 Reed, H. S. [B 236, 249], 67, 72, 199, 247.
 Reiset, M., 192.
 Remy, Th. [B 237], 199, 204, 261, 263.

- Rettger, L. F., 186.
 Rice, Frank E. [B 238], 112.
 Richards, E. H. [B 238a, 241i and k], 76, 179, 190, 195, 203, 228, 256.
 Richmond, T. E., 211.
 Rigg, Th., 345.
 Rindall, A. [B 239], 113.
 Risler, E., 346.
 Robbins, W. J., 212.
 — W. W., 254.
 Robertson, G. Scott, 312.
 — R. A., 138, 139.
 Robinson, G. W. [B 240], 100, 101, 118, 330, 334, 345, 347, 353.
 — R. H., 185.
 Rohland, P., 104, 106.
 Römer, H. [B 120d, 309h], 297.
 Rösing, G. [B 237b], 199.
 Rosso, V., 59.
 Ross, Ronald, 289.
 Russell, E. J. [B 121, 146d, 241], 27, and elsewhere.
 Ruston, Arthur G. [B 71], 82, 268.
 SABASCHNIKOFF, A. [B 181c], 279.
 Sackett, W. G., 211, 263.
 Salisbury, E. J. [B 242], 241, 305, 314.
 Salter, R. M. [B 243], 81, 352.
 Sanderson, J. C., 89.
 Sandon, H., 289.
 Sangiorgi, C., 289.
 Satterly, J., 89.
 Saussure, Théodore de [B 244], 9, 18, 20, 175.
 Saw, M. P., 351.
 Scales, F. M. [B 185c], 258.
 Scheele, Carl Wilhelm, 9.
 Schloesing, Th. [B 244, 5], 23, 122, 118, 161, 175, 210.
 — — fils [B 246, 7], 25, 227, 255.
 Schneider, Felix, 170.
 — Ph. [B 248], 201.
 Schneidewind, W. [B 156a], 282.
 Schollenberger, C. J. [B 4], 118, 119, 120.
 Schonbein, C. F., 208.
 Schreiner, O. [B 249-52], 141, 157, 247, 248, 282.
 Schröder, J. [B 215a], 69.
 Schübler, Gustav, [B 254], 12, 14.
 Schulze, B., 73.
 Schultz-Lupitz [B 255], 314.
 Schumacher, W., 173.
 Searle, A. B., 106.
 Seaver, F. J., 282.
 Sebelien, J. [B 234], 136.
 Seelhorst, C. von [B 256-8], 38, 44, 45, 48, 128, 180.
 Senebier, Jean [B 259], 9.
 Sestini, F., 216.
 Shantz, H. L. [B 55b], 43, 47, 224, 220.
 Sharp, L. T. [B 136b, c, 260], 80, 110, 125, 127, 238, 349.
 Shedd, O. M., 212.
 Sherman, J. M. [B 261], 283, 285, 290, 293, 295.
 Shive, J. W. [B 262], 79, 80.
 Shorey, E. C. [B 249, 261], 121, 141.
 Shull, C. A. [B 261], 53, 167, 222, 221, 226.
 Shutt, F. T. [B 265], 44, 181, 310.
 Sibirtzev [B 266], 303.
 Sigmund, Alexius A. J. von, [B 266a], 157, 344, 352 (also called A. de Sigmund).
 Sigmund, Wilhelm, [B 267], 86.
 Simmermacher, W. [B 244f], 244.
 Sjollem, B., 170.
 Skene, M., 306.
 Skinner, J. J. [B 179, 252], 248.
 Smalley, H. R., 112.
 Smith, Angus, 192.
 — Geoffrey, 293.
 — J. G. [B 97], 100.
 — Norman, 210.
 — N. R. [B 185], 197, 300.
 — Otto M., 162.
 — R. E. [B 60d], 270.
 Snyder, Harry [B 268], 120, 138, 147, 181.
 Soderbaum, H. G., 58.
 Söhngen, N. L. [B 260], 213, 249.
 Sørensen, S. P. L., 115.
 Sostegni, L., 140.
 Sothers, D. B. [B 204], 164, 165.
 Sprengel, Carl [B 270], 14, 129.
 Stevens, F. L. [B 271], 190, 264.
 Stewart, R. [B 113b], 44, 50, 86, 146, 173, 272.
 Stiles, W. [B 272], 51, 238.
 Stoddart, C. W. [B 307].
 Stohmann, F., 155.
 Stokes, G. C., 353.
 Stoklasa, Julius [B 273-5], 72, 75, 91, 177, 197, 198, 199, 206, 209, 211, 209.
 Stormer, K. [B 135b, c], 276, 281.
 Straňák, Franz [B 275b], 197, 198.
 Stremme, H., 165.
 Strutt, R. J., 89.
 Stutzer, A. [B 276], 206.
 Suchtelen, F. H. H. van, 123, 176.
 Suchting, H. [B 278b].
 Sutton, M. H. F., 91.
 Suzuki, Shigehiro [B 277], 76, 208.
 Swanson, C. O., 181.
 TACKF, Br. [B 278], 113, 136, 143.
 Tadokoro, T., 170.

- Tansley, A. G. [B 279], 134.
 Tartar, H. V., 185.
 Tatlock, R., 352.
 Temple, J. C., 263, 273.
 Tenant, Smithson, [B 280], 86.
 Ternetz, Charlotte, 259.
 Thaer, A. von, 11.
 Thaysen, A. C. [B 140g], 249.
 Theiler, A., 318.
 Thiele, R. [B 281], 203, 232.
 Thompson, H. S. [B 282], 150.
 Thomson, D., 289.
 Thornton, H. G., 293.
 Thurmman, H. [B 224a].
 Totttingham, W. E. [B 283], 79, 212.
 Traaen, A. E., 272.
 Treub, 255.
 Truog, E. [B 285], 74, 81, 113.
 Tucker, M. [B 256].
 Tulaikoff, N. M. [B 266, 284], 48.
 Tull, Jethro [B 286], 5.

 UNDERWOOD, Lillian M. [B 121d], 51,
 52, 173, 238.

 VBITCH, F. P. [B 287], 119.
 Vermuyden, C., 308.
 Ville, Georges, [B 288], 19, 192.
 Vincent, C., 120.
 Virgil, 184.
 Vitek, Eugen, [B 275b], 197, 198.
 Voelcker, A. [B 289], 128, 150.
 — J. A. [B 290], 73-6, 78, 86.
 Vogel, I. [B 104], 198.

 WADK, H. R. [B 97], 100.
 Waggamann, W. H., 157.
 Wagner, P. [B 291], 193, 195, 209.
 — R., 212.
 Waksman, Selman A. [B 292], 186, 187,
 257, 258, 259, 260, 276, 290, 294.
 Wallerius, Johan Gotschalk, [B 293], 7.
 Warburg, O., 57.
 Ward, Marshall, [B 294], 205.
 Warrington, R. [B 166b, 295-97], 23,
 180, 189, 190, 209, 298, 357.
 Warth, F. J., 351.
 Way, J. T. [B 298], 17, 22, 150, 153,
 155.
 Waynick, D. D., 262, 349.

 Weber, C. A. [B 299], 134.
 Webster, T. A., 200, 255.
 Weevers, T., 72.
 Weinhold, A. [B 300].
 Weir, W. [B 300a], 144.
 Weis, Fr. [B 301], 146.
 Westermann, T. [B 302], 139.
 Wheeler, H. J. [B 303], 116.
 Whiting, A. L., 191, 206, 207.
 Whitney, M. [B 304-6], 27, 124, 172,
 173, 233, 238, 247, 343.
 Whitson, A. R. [B 307], 321.
 Wieler, A., 82.
 Wiegner, Georg, [B 308], 97, 156.
 Wigham, J. T., 89.
 Wild, L. J., 119.
 Wiley, H. W., 355.
 Wilfarth, H. [B 130c, d: 309], 24, 19.
 — 59, 196, 204, 297.
 Willcox, W. H., 194.
 William, H. F. [B 186], 100, 191.
 Williams, Bruce, 199.
 Willstätter, Richard, [B 310], 75.
 Wilms, J. [B 258], 128.
 Wilson, G. W. [B 188], 259.
 — J. B., 78.
 — J. K., 207.
 Wimmer, G. [B 130d, 309b], 297.
 Winogradsky, S. [B 311-12], 23, 184,
 190, 196, 260.
 Wise, L. E. [B 105c], 114.
 Withers, W. A. [B 271, 313], 190, 262,
 263.
 Wojtkiewicz, A. [B 314], 279.
 Wolff, E. [B 315], 77.
 Wolkoff, M. I. [B 316], 79, 80, 161.
 Wollny, E. [B 317-18], 26, 139, 175,
 176, 232.
 Wood, T. B. [B 319-20], 234.
 — J. T., 194.
 Woodward, J. [B 321], 4.
 Woronin, M. [B 322], 25.

 YOUNG, Arthur, 6.

 ZALESKI, W., 35.
 Zsigmondy, R., 99, 148, 160.
 Zwaardemaker, H., 72, 91,
 Zyl, J. P. van, [B 323], 125, 127.

SUBJECT INDEX.

- ABSORPTION compounds in soil, 104.
 — of nutrients by plants, 296, 357.
 — — substances by soil, 17, 149 *et seq.*
 — — — — — chemical explanation (Way), 153.
 — — — — — colloidal explanation, 155.
 — — — — — combined chemical and physical explanation (Knop), 154.
 — — — — — physical explanation (Liebig), 154.
 — — — — — Equations expressing: amount, 150.
 — — — — — rate, 157.
 Acidity, effect on plants, 81.
 — in soil, 109. See also Soil Acidity.
 — — atmosphere, effect on plants, 82.
 — methods of studying; hydrogen ion concentration, 113; titration, 113.
 Acids, dilute, action on soil, 157 *et seq.*, 234.
 — — use in soil analysis, 234, 334.
 — effect on activity of micro organisms in soil, 268.
 — — — plant growth, 81, 268.
 — supposed excretion by plant roots, 16, 233.
 Actinomyces in soil, 259.
 — producers of humus, 177.
 Adsorption, 156.
 — equation expressing, 149, 156.
 Aeration of soils, effect on plant growth, 51, 84.
 — swamp soils assisted by algæ, 256.
 Agricere, 282.
 Agriculture, early literature of, 1.
 Air, effect on plant growth, 9.
 — of vegetation on, 8, 10, 20.
 — in soil, composition of, 227.
 — — — volume of, 220.
 — supply to plant roots, 51.
 — — — — in swamp soils, 256.
 Algæ in soils, 254.
 Alkali soils, 74, 86, 94.
 Alkali soils, bacterial activity, 274.
 Alkalis necessary for plant growth, 15, 18.
 — supposed production by plants, 8, 10.
 Alumina in soil, 338.
 Aluminium, beneficial in small quantities, 56, 75.
 — harmful in larger amounts, 84.
 Amino-acids produced in soils, 185.
 Amino-nitrogen in soils, 147.
 Ammonia, assimilation by algæ, 256.
 — — — fungi, 249.
 — — — micro organisms, 210 *et seq.*
 — — — plants, 57.
 — in soil, determination of, 349.
 — — — amount of, 146.
 — nutritive value to plants, 58.
 — production in soil, 185 *et seq.*
 — — — organisms effecting, 187.
 — — — by fungi, 259.
 — toxic effects in larger quantities, 58, 80.
 Ammonifying power, 263.
 Ammonium salts, absorption by soil, 155 *et seq.*
 — sulphate acidifies soil, 116.
 Amoebæ in soil, 289 *et seq.*
 Analysis of plant ash and study of plant nutrients, 7.
 — — — soil and manurial requirements, 326, 334.
 — — — mechanical and chemical contrasted, 342.
 — — — methods of, 347.
 Antagonism of ions (bacteria), 274.
 — — — (plants), 79.
 Arid conditions, value of phosphates in, 65.
 — soils, comparison with humid: mineral composition, 100.
 — — — organic matter, 149.
 Arsenic compounds, effect on micro organisms, 84.
 — — — — plant growth, 84.
 — — — — oxidation by bacteria, 84.

- Artificial manures, 18, 19, 20.
 Ash constituents of plants; composition of, 10.
 — — — — — essential to growth, 10, 14.
 — — — — — functions of, 10.
 — — — — — importance as manure (see also Mineral constituents), 2, 15, 16.
 Asparagine as plant nutrient, 57.
 Aspartic acid as plant nutrient, 57.
 Assimilation, effects of temperature on, 35.
 Auximones, 236.
 Availability of mineral nutrients, 234, 245, 353.
 Azotobacter. See Nitrogen fixation.
 — activity in natural conditions, 200.
 — effect of humus on, 199.
 — test for soil acidity, 212.
 — and clostridium, relative distribution of, 204.
 BACTERIA as makers of plant food, 26, 175, 216.
 Bacterial activity and nitrate production, 270 *et seq.*
 — — — — — soil productiveness, 176, 216, 260 *et seq.*
 — numbers in soil, effect of external conditions on, 272, 275 *et seq.*, 286.
 — — in field soils, 275 *et seq.*, 292.
 — — in soil, 217, 262, 264 *et seq.*, 276, 292.
 — — — — — not clearly related to plant growth, 266.
 — — rapid fluctuations in, 270, 292.
 — — under different crops, 297.
 Bacteriotoxins in soils, supposed, 249.
 " Bake " land, 241.
 Barium salts, effect on plant growth, 74.
 Basicity in soils, harmful effect of lack of, 117.
 Black soils, properties of, 307, 310.
 Bleisand, 163.
 Bones, fermentation of, 211.
 Boron, harmful in large amounts, 78.
 — helpful in small quantities, 56, 78.
 Brownian movement of clay particles, 105.
 Buffer action, 115.
 CALCIUM salts and plant growth, 74.
 Calcareous soils, 94, 303.
 — — characteristics of plant growth on, 304.
 Calcareous plants, 74, 304 *et seq.*
 Calcifuges, 74, 304 *et seq.*
 Calcium in plants; association with nitrogen, 74.
 — — — — — more in leaf than in seed, 74.
 — carbonate, amount desirable in soil, 119.
 — — effect in soil, flocculation, 117.
 — — — — — neutralisation of acid, 117.
 — — — — — other effects, 117, 119, 329.
 — — — on soil organisms, 273.
 — — — — — plant, small quantities, 239.
 — — — — — excess, 86, 304.
 — — — not always essential to fertility, 118.
 — — — production in soil, 296.
 — — — rate of removal from soil, 119.
 — compounds in soil, 121.
 — oxide. See Lime.
 — salts, effects on plant growth, 74, 78.
 — — — — — soil organisms, 274.
 — sulphate. See Gypsum.
 Carbohydrates, absorbed and utilised by plants, 57.
 — effect on ammonia production, 186.
 — — — denitrification, 202, 209 *et seq.*
 — — — nitrogen fixation, 198.
 — — — soils, 201.
 — elaboration in plants affected by potassium salts, 70.
 — transformation in plants affected by phosphates, 67.
 Carbonates, amount in soil, 337.
 — determination in soil, 335, 350.
 Carbon cycle in soil, 175.
 — nitrogen ratio in plant residues, 175.
 — — — — — soil, 175, 273.
 — dioxide, effects of variation on plant growth, 57.
 — — evolution in soil, 175, 177; relation to ammonia production, 185.
 — — — — — inhibiting effects on germination, 85.
 — — in soil air, variations in, 227, 277.
 — — necessary for plant growth, 10.
 — — percentage in soil atmosphere, 227.
 — — toxic effect on root, 51.
 — — variations in atmosphere, 57.
 — source of, for plants, 10, 12, 56.
 Cardiganshire, damage done by lead mines, 85.
 Carr, 134.

- Catalytic actions of soils, 215.
 Cellulose, decomposition in soil, 177.
 — — — by fungi, 258.
 — — — by *Spirochaeta cytophaga*, 177.
 Chalk soils, 120, 306 *et seq.*
 Charlock, spraying for, 83.
 Chemical analysis of soil, 233.
 Cheshunt Experimental Station, 71.
 Chlorides and plant growth, harmful in larger amounts, 73, 75, 76.
 — — — necessary in small quantities, 56.
 Chlorophyll a magnesium compound, 75.
 Chlorosis, 86, 304.
 Clay as electro-negative colloid, 104, 161.
 — — — semi-permeable membrane, 105.
 — — — colloidal (Schloesing's) preparation of, 148.
 — — — composition of, 101 *et seq.*
 — — — definition of, 104.
 — — — effects in soil, 106.
 — — — justification of British definition, 99.
 — — — particles, constitution of, 162.
 — — — properties of, 104 *et seq.*
 — — — relation to K_2O content, 340.
 — — — soils, 310.
 — — — characteristics of plant growth on, 312.
 — — — need some excess of calcium carbonate, 119, 336.
 — — — water supply in, 219.
 — — — two groups of, 101.
 Climate and crops, 45.
 — — — a factor in determining soil type, 99, 303.
 — — — — — fertility, 331.
 Clostridium and azotobacter, relative distribution of, 204.
 Coarse sand, composition of, 102.
 — — — effect in soil, 108.
 — — — properties of, 108.
 Coastal soils, 101.
 Colloidal clay, preparation of, 148.
 Colloids in soil, effect in determining plant habitats, 239.
 — — — estimation of, 163.
 — — — importance, 149, 172.
 — — — influence on micro-organisms, 239.
 — — — — — reactions, 168.
 — — — properties of, 148.
 Competition between plants, effect on flora, 241.
 — — — balance in, 241.
 Composition of soil particles, 102.
 Compound interest law (V. H. Blackman), 28.
 Compound particles in soil, 170, 171, 303.
 Condition and fertility, 320.
 Constitution of clay, 162.
 — — — soil, 170.
 — — — particles, 172.
 Cooper-Hewitt mercury lamp and plant growth, 88.
 Copper salts harmful to plant growth, 83.
 — — — use as plant poisons, 83.
 Crenic acid, 141.
 Crops, distribution of; influence of rainfall, 45.
 — — — — — temperature, 45.
 — — — specially suited to certain soils, 240.
 Cultivation, exhaustion due to continuous, 321.
 — — — loss of nitrogen during, 181.
 Decomposition of organic matter in soil, 175 *et seq.*
 Deflocculation. *See* Flocculation.
 Denitrification, 208.
 — — — not extensive in normal soils, 209.
 Depth of soil, importance of, 306.
 Dicyanodiamide, toxic to plants, 85.
 Disease organisms in soil, 253.
 — — — resistance as affected by soil conditions, 53, 61, 70, 71.
 Dominant constituents of fertilisers, 19.
 Drainage water, composition of, 127, 152.
 — — — nitrogen lost in, 178, 209.
 Dried soil and productiveness, 169.
 Drought, effect on soil reactions, 275.
 Dry farming, 218.
 EARTH the "principle" of vegetation, 4.
 Earthworms in soil, action of, 136, 137.
 Ecological classification of humus, 133.
 Ecology, province of, 43.
 Edinburgh Society for Improvement of Arts, 6.
 Eelworms in soil, 253.
 Efficiency values of plant nutrients ("Wirkungswert"), 33.
 Elective method, 196.
 Electric discharge, effect on plant growth, 87.
 Electrolytes, effect on clay, 105.
 Electro-osmosis, 161.
 Emulsoids, 160.
 Energy relationships; micro-organisms, 129, 252, 272.
 — — — ammonifying, 186.

- Energy relationships; micro-organisms,**
 denitrifying, 209.
 — — — nitrifying, 188.
 — — — nitrogen-fixing, 197, 199, 201.
 — — — other groups, 250 *et seq.*
 — — — — algæ, 252.
 — — — — bacteria, 128, 176, 252.
 — — — — fungi, 252.
 — — — — protozoa, 252.
 — — plants, 128.
 — — sources in soil, 93, 129.
 — supply and soil population, 176, 211.
 Engrais complémentaires, 76.
 Eremacausis, 23.
 Excretions from plants, possible toxic, 244 *et seq.*
- Factors affecting the growth of plants,**
 30, 38.
 Faeces and nitrogen-fixation, 203.
 Fallowing, effect on nitrates in soil, 297 *et seq.*
 — — — soil, 15, 18, 297.
 — — — harmful effect on fen soils, 310.
 — losses during, 180.
 Farmyard manure as fertiliser, 19, 236.
 — — effect on clover crop, 207.
 — — increases moisture content of soil, 132.
 — — losses during storage, 193.
 — — loss of nitrogen in soil, 181.
 — — retained in surface soil, 152.
 — — and solubility of phosphates, 212.
 — — — bacterial numbers, 269, 273, 276.
 — — — denitrification, 209.
 Fattening fields in Romney Marsh, 317.
 Fen, 134, 307, 308.
 Fertility, transfer from new to old countries, 318.
 Field trials, necessity for, 19, 324.
 Fine sand, composition of, 102.
 — — effect in soil, 108.
 — — properties of, 108.
 — — silt, composition of, 102.
 — — effect in soil, 107.
 — — properties of, 107.
 Flagellates in soil, 291 *et seq.*
 Flocculation, absorption hypothesis, 161.
 — electrical hypothesis, 161.
 — of clay, 105, 160 *et seq.*
 — — silt, 160 *et seq.*
 — reversibility of, 161.
 Flooding, effect on soil, 325.
 Flora, plant, factors determining, 301.
 — — and soil reaction, 240.
- Fluorides and plant growth, harmful in larger amounts, 76.**
 — — — necessary in small quantities, 56, 76.
 Folding, 306.
 Food supply and plant growth, 30, 55.
 — — effect of on water requirements of plants, 48.
 Forest soils, humus of, 136.
 Fractions obtained during mechanical analysis, 98, 326.
 Frost, late, 303.
 — — effect on soil bacteria, 279.
 Fungi in soils, 137, 256 *et seq.*, 282.
 — — — favoured by acid conditions, 243.
 — — — producers of humus, 177.
 Fulvic acid, 141.
 Fungoid pests, liability to, 53, 61, 72.
- GERMINATION, capacity of buried weed seeds, 85.**
 — — — seed, 54.
 — — effect of salts on, 86.
 — — — CO₂ on, 85.
 Glacial soils, 100.
 Glasshouse practice, effects of temperature, 46.
 — — — watering, 46.
 Glutamic acid as plant nutrient, 57.
 Grain, composition of. See Seed.
 — proportion to straw, factors affecting, 61.
 — — — increased by phosphates and silicates, 77.
 Grass, growing, effect on fruit trees, 246.
 Gravel, composition of, 102.
 — effect in soil, 109.
 — properties of, 109.
 Green manuring, 314.
 Gypsum, effect on plants, 74, 79, 86.
 — — — soils, counteracts alkalis, 74.
 — — — supply of potassium salts, 152.
- HEATED soil, changes in, 169, 281.**
 Hochmoor, 134.
 Hoeing as manure (Tull), 5.
 Hormones, 87.
 Hot water treatment for forcing plants, 88.
 Humic acid, composition of, 138.
 — — fractionation, 140, 141.
 — — preparation and properties, 139.
 — — proof of acid nature, 143.
 — — protective effect on flocculation, 162.

- Humic, 141, 146.
 — hydrolysis of, 146.
 Humus, 133, 137, 303. See also Organic matter in soil.
 — analysis of, 138.
 — artificial production of, from dihydroxyfurfuraldehyde, 143.
 — — — — — quinone, 143.
 — — — — — sugar, 142.
 — colloidal properties, 140.
 — effect on iron compounds in soil, 165.
 — formation in soils, from cellulose, 141, 177.
 — — — — — field observations, 136 *et seq.*
 — function in soil, 15, 130, 144.
 — not effective in denitrification, 209.
 — of field soils, 137.
 — — — — — similarity to peat, 137.
 — — forest soils, 136.
 — relation to Azotobacter, 199.
 — soils, 94, 307.
 — — characteristics of plant growth on, 310.
 — soluble, supposed necessity for fertility, 143.
 — supposed food of plants, 7, 8, 12, 15.
 "Hungry" soils, 108, 312.
 Hydrogen ion concentration of plant juices, 81.
 — — — — — soil solution, 116.
 — — — — — in relation to plant growth, 81.
 Hydroxyl ion more toxic than hydrogen ion, 81.
 Hygroscopic coefficient, 223.
 — — relation to other moisture coefficients, 226.
 — water, 166 *et seq.*
 Hymatomelanic acid, 141.
 IMPROVEMENT of exhausted soils, 321.
 — — — — — soil, methods of, 320.
 Injurious factors (to plants), effect of, 42, 80.
 — substances (to plants), 80.
 Inoculation of soil with Azotobacter, 203.
 — — — — — nodule organisms, 208.
 Iodides and plant growth, beneficial in small quantities, 56, 76.
 — — — — — harmful in larger amounts, 76.
 Ions, antagonism of, 79.
 — complex equilibrium in plant cell, 79.
 Iron compounds in soil, 338.
 — — — — — part played in pan formation, 163.
 — — — — — effect on plant growth, 75, 84.
 Irrigation, 50, 86.
 — and varying requirements of plants, 50.
 — — — — — effect on soil organisms, 272.
 — — — — — injurious effects of excessive, 50.
 Iso-electric point, 161.
 LAMZIEKTE, 318.
 Law of minimum, Liebig, 16.
 — — — — — Mitscherlich, 28.
 Leaching, effect on soil, 99.
 Lead mines, damage done to vegetation by, 85.
 Leguminous crops, effect on soil, 184, 208.
 — — — — — nitrogen fixation, 21, 207.
 Liebig's patent manure, 10, 17.
 Light and plant growth, 54.
 — — — — — indirect effect on soil, 55.
 Lime as a sterilising agent, 273.
 — — — — — effect on soil, 11. See also Calcium carbonate.
 — — — — — organisms, 273.
 — — — — — indications of lack in soil, 336.
 — — — — — magnesia ratio, 75, 339.
 — — — — — requirement of soil, 114, 119.
 — — — — — determination of, 350.
 Limiting factors, 28, 38.
 Lithium salts, harmful to plant growth, 73.
 Loams, 315.
 — — — — — characteristics of plant growth on, 315.
 Lodging of cereal crops, 317.
 Loess soils, 100.
 Lysimeter experiments, 178, 180.
Magna unguinosum, the principle of vegetation, 4.
 Magnesian limestone, effect as fertiliser, 86.
 Magnesium associated with formation of oil in plants, 75.
 — — — — — carbonate, effect on soil organisms, 273.
 — — — — — compounds in soil, 339.
 — — — — — in seed, 75.
 — — — — — salts, effect on plant growth, 75, 86.
 — — — — — — — — — supply of potassium salts, 151.
 Manganese salts, beneficial effect on nodule organisms, 207.
 — — — — — — — — — plant growth, 56, 76.

- Marsh gas, oxidation of, in paddy soils, 213.
- Mathematical expressions, for plant growth, 31, 34, 42.
- — search for, 27.
- — value of, 28.
- Matière noire (humus), 138.
- — supposed index of fertility, 143.
- Maturation, 51.
- Mechanical analysis, defects of ordinary, 95.
- — difficulty of interpreting quantitatively, 170.
- — fractions obtained during, 98.
- — interpretation of, 326.
- — methods, 353.
- — not applicable to chalk or peat soils, 344.
- — Oden's distribution curve, 95.
- Melanoids, 141.
- Mercury vapour lamp, effect on plant growth, 88.
- Methods of investigation; bacteriological, 260.
- — — correlation, 104, 130.
- — — modern combined, 28.
- — — quantitative, 9.
- — — statistical, 18, 29.
- Micro-organic population of soil, effect on productiveness, 294.
- Micro-organisms in soil; active and resting stages, 216, 290.
- — — action of plant on, 296.
- — — agents causing decomposition, 175.
- — — — producing plant nutrients, 27.
- — — general relationships, 252.
- — — groups of, 250 *et seq.*
- — — methods of investigation, 257 *et seq.*
- — — relation to growing plants, 129, 251, 252, 260, 294, 296.
- — — sources of energy for, 129.
- Mineral constituents of plants, functions of, 19.
- — — list of essential, 19.
- — — origin of, 9.
- — part of soil, 94 *et seq.*, 351.
- — soils, 94.
- Mineralogical investigations of soil, 100.
- Minimum, law of, Liebig, 16, 28.
- — — Mitscherlich, 28.
- Mining (metal-), injury to vegetation caused by, 85.
- Mixed crops, 249.
- Moisture in soil, amounts of, 200. See Water in soil.
- — equivalent of soil, 224.
- Molkenböden, 163.
- Moorland soils, 307.
- — bacterial activity in, 269, 307.
- Muck land, 310.
- Mull, 136.
- Mycorrhiza, 253.
- Myxomycetes, 253.
- NEMATODES, free living, 252.
- — parasitic, 253.
- Niedermoor, 134.
- Nitrate immobiliser in soil, 179.
- Nitrates, assimilation by micro-organisms, 210 *et seq.*
- — — algæ, 256.
- — as plant food, 22.
- — contrast between production and destruction, 209.
- — effect on bacterial action, 199, 275.
- — essential plant food, 22.
- — formation in soil, 21. See also Nitrification.
- — — — effect of growing plant on, 297.
- — — — of season, etc., 276.
- Nitrates and plant growth:
- — — effect of water supply, 10.
- — — qualitative relationships, 57, 61.
- — — — affected by potassium salts, 63.
- — — quantitative relationships, 24, 40, 59, *et seq.*
- — — (See also Saltpetre.)
- — in soil, alleged catalytic formation of, 216.
- — — amounts of, 145.
- — — decomposition of, 300.
- — — determination of, 348.
- — — maximum producible, 178.
- — — removal of, 178, 180, 235.
- — — seasonal fluctuations, 146.
- — — supply oxygen to organisms, 209.
- Nitre beds, 21.
- — resemblance to fertile soil, 11.
- Nitrification, 187 *et seq.*, 216.
- — an autocatalytic process, 188.
- — bacterial origin demonstrated, 23.
- — culture solutions, 188.
- — effect on soil phosphates, 191.
- — influence of organic matter, 190.
- — in sewage, more rapid than in soil, 215.
- — soil, limited by rate of ammonia production, 188.
- — not an oxidase action, 188.
- — organisms causing, 188, 191.
- — relation to soil fertility, 22.

- Nitrification, supposed chemical origin, 23.
 — two stages demonstrated, 23, 188.
 Nitrifying power, 262, 300.
 Nitrites, assimilated by plants in small quantities, 59.
 — bacterial production from nitrates, 208.
 — harmful in larger amounts, 85.
 Nitrobacter. See Nodule organism.
 Nitrogen, determination of, 348.
 — evolution of gaseous, in decomposition of organic matter, 191.
 — fixation of, 182, 195. See also Nitrogen fixation.
 — fixing power, 265.
 — gaseous, supposed assimilation by plants, 14.
 — — supposed evolution from soil, 182.
 — in plant, association with calcium, 74.
 — nutrition, distinction between leguminous and non-leguminous plants, 18, 21, 24.
 — recuperative agencies in soil, 182.
 — source of, for vegetation, 10, 14 *cf seq.*, 18, 20.
 — content of soils; Broadbalk, 153, 183.
 — — — relation to loss on ignition, 335.
 — — — — upper and lower limits, 184.
 — — — — Wilderness, 183.
 — — — grain, effect of length of ripening period, 54.
 — — — increased by magnesium oxide and carbonate, 75.
 — — — — sodium hydrate and carbonate, 73.
 — — — — unaffected by many salts, 73.
 — cycle in soils, 175, 178.
 — fixation, attempts to induce in soils, 201.
 — by electric discharge, 196.
 — — free-living organisms—
 Algae, 200, 255.
 Azotobacter, 197.
 Clostridium, 196.
 — fungi, 259.
 — nodule organisms, 25, 204.
 — other organisms, 200, 208.
 — in soil, 182.
 — — estimated amount of, 207.
 — in soils, compounds present, 145.
 — — — loss of, 178, 181.
 Nitrogen in soils, percentage present, 335.
 — — — relation to fertility, 334.
 Nitrogenous nutrients for plants, 18, 22, 57.
 Nodule organism, artificial culture of, 204, 206.
 — — entry into plant, 205.
 — — isolation from soil, 205.
 — — life cycle, 204.
 — — specific nature of, 25.
 — — stimulated by manganese compounds, 207.
 Nodules on roots of leguminosae contain bacteria, 21, 25.
 Normal conditions in heavy soil, 249.
 Nutrient solution, effect of concentration on plant growth, 238.
 Nutrients become toxic when given in larger quantity, 56.
 — needed in large quantities, 56.
 — — small quantities only, 56, 236.
 — quantity absorbed by plants from soil, 284, 357.
 — raw materials out of which plant food is made, 55.
 Nutrition of plants, effect of water supply, 38 *cf seq.*
 Nutritional disturbances in plants, 236, 304.
 ORGANIC compounds absorbed and utilised by plants, 57.
 — — decomposition in soil, 212.
 — — effect on plants, 248.
 — matter in soil, chemical properties of, 138 *cf seq.*
 — — — colloidal properties of, 130.
 — — — decompositions, summary of, 214.
 — — — determination of, 348.
 — — — effects of, 130, 329.
 — — — — on fertility, 130, 334.
 — — — — on water supply, 131, 132.
 — — — — partially decomposed, 140.
 — — — — undecomposed, 130.
 — — — — fractionation of, 141.
 — — — — masks effects of clay and sand, 132.
 — — — — nature of, 129.
 — — — — original deposit, 129.
 — — — — recent formation, 129.

- Organic matter in soil, relation to micro-organic population, 128, 129, 252, 272.
- Ortstein, 137, 163.
- Osmotic pressure; cell sap, 46, 222, 237.
- in relation to soil moisture, 46.
- root sap, 222, 237.
- soil solution, 125, 237.
- — — and classification of habitats, 237.
- Oxidation in soil, 175.
- potential in soil, 177.
- relation to fertility, 176, 283.
- Oxygen, dissolved, effect on bacterial action, 275.
- supply necessary for root, 51.
- to plant root in swamp soils, 213.
- PADDY soils, 212, 300.
- Pan, composition of, 164.
- formation, 137, 162 *et seq.*
- as colloidal phenomenon, 165.
- chemical hypotheses, 163.
- Partial sterilisation of soil, 280 *et seq.*
- Pasture soils, humus of, 137.
- nitrates in, 146.
- Pathological conditions, possible nutrition effects, 236.
- Peat, 133.
- English types, 134, 135.
- Irish types, 135.
- Scotch types, 135.
- Peat; acidity, cause of, 111.
- chemical analysis of, 136.
- in relation to pan formation, 163.
- soils, 94, 307.
- assimilation of ammonia in, 210.
- denitrification and manuring, 210.
- effect of lime on, 119, 210.
- water supply in, 219.
- Perchlorates toxic to plants, 85.
- Permeability in soil, 105.
- Permutit, 156.
- Petrographic methods of soil analysis, 121.
- P_H value, definition of, 115. See Hydrogen ion concentration.
- Phenol, decomposition of, in soil, 212, 216.
- Phosphate exhaustion, 321.
- Phosphates, effect of bacteria on, 191, 211.
- on soil bacteria, 274.
- in plants, economised by presence of silica, 78.
- in soil, 120, 341.
- — — determination of, 352.
- Phosphates in soil, reaction with dilute acids, 157.
- and plant growth, necessity for, 8, 15, 18.
- — — qualitative effects, 64.
- — — quantitative relationships, 3, 64.
- Phosphatic fertilisers: increase quality in crops, 67.
- use on cereals, 65.
- — — clay soils, 64, 312.
- — — dry soils, 65.
- — — fen soils, 309.
- — — grassland, 67, 183.
- — — root crops, 64.
- Phosphorus compounds in soil, 120.
- effect on cell division, 67.
- — — starch transformations, 67.
- — — function in cell, 66.
- more in seed than in leaf, 68.
- Physical properties of soil, early studies, 12.
- Physiological balance of inorganic nutrients in culture solutions, 78.
- — — — — soil, 80.
- grouping of soil organisms, 261.
- Physiology, plant, foundation of, 9.
- Plant food, amount in soil, 233.
- available, 233.
- growth, effect on soil, 296.
- — — soil organisms, 297.
- — — factors affecting, 30 *et seq.*
- in relation to soil types, 315.
- optimum ratio of nutrients, 80.
- periods in, 296.
- relation to concentration of soil or culture solution, 80.
- materials from which it is produced, 6.
- nutrients, circulation between plant and soil, 93.
- nutrition, methods of studying, 7.
- — — realisation of complex nature of, 7.
- residues, action in soil, 213.
- — — decomposition in soil, 214.
- Plants, supposed resemblances to animals, 8.
- Plasticity of clay, effects of, 106.
- — — theories of, 106.
- Plating methods, soil bacteria, 261, 265.
- Ploughsole, 166.
- Poisons, inorganic, effect on plants, 80 *et seq.*
- organic, effect on plants, 248.
- Pore space, 220.
- Pot cultures, introduction of, 7.

- Pot cultures, modern methods, 356.
 Potash in soil, determination of, 352.
 Potassic fertilisers, effect on leguminous crops, 72.
 — — value for thin soils or dry districts, 340.
 — — — in unfavourable seasons, 71.
 Potassium compounds in soil, 120, 339.
 — — — distribution among soil particles, 121.
 — — reported harmful effect on soil, 116.
 — — function in cell, 72.
 — — in plants, economised by presence of sodium, 73.
 — — salts, absorption by soil, 157.
 — — effect on bacterial action, 274.
 — — influence on nitrogen effects, 63.
 — — necessary for plant growth, 7.
 — — qualitative effects on plant, 69.
 — — quantitative relationships, 31.
 — — suggested replacement in cell by equi-radioactive elements, 72.
 Potatoes, quality in, 318.
 Potsherds, effect of adding to soil, 52.
 Prairie soils, loss of nitrogen from, 181.
 Principles of vegetation, search for, 2.
 Protein content of grain. See Nitrogen.
 — — metabolism; relation to calcium, 74.
 Protozoa in soil, 288 *et seq.*
 — — — inverse relation to bacteria, 292.
 — — — numbers of, 291.
 Putrefactive power (Remy), 263.
 RADIO-ACTIVITY and potassium supply, 72.
 — — of soil, 89.
 Radium, effect of, on plant growth, 89.
 Rainfall and crops, effect, 45.
 — — effect on scheme of manuring, 341.
 — — — soil, 119, 235, 330.
 Rain water; ammonia and nitrate in, 18.
 — — — chlorine content, 76.
 — — — dissolved oxygen in, 228.
 — — — sulphates in, 76.
 Reaction of soil; methods of controlling, 244.
 Reactive inorganic constituents of soil, 109, 215.
 Reclamation of clay soils, 312.
 — — sandy soils, 314.
 Renewal of plant nutrients, effect of rate of, 239.
 Respiration of plants, general phenomena, 10.
 Resting period of plants, 88.
 Ripening processes hastened by phosphates, 65.
 — — — drought, 65.
 Rohhumus, 138.
 Rothamsted experiments, commencement of, 17.
 — — — results, 18, and many subsequent pages.
 Root, activity of, makes soil alkaline, 206.
 — — — crops, use of phosphatic fertilisers, 64.
 — — — development, increased by phosphates, 64, 341.
 — — — marked in sandy soils, 316.
 — — — impeded in clay soils, 64.
 — — — excretion, nature of, 33, 233.
 — — — of mineral matter, 296.
 — — — possible toxic, 244.
 — — — formation of, increased by aeration, 51.
 — — — — — calcium salts, 74.
 — — — — — phosphates, 64.
 — — — — — influence of soil type, 64.
 — — — — — water supply, 44.
 — — — functions of, 10.
 — — — sap, acidity of, 81.
 — — — concentration of, 222, 237.
 — — — osmotic pressure of, 222, 247.
 Rotation of crops, 184, 244.
 — — — not essential, 5.
 — — — statistics of, 13.
 SALTETRE promotes vegetation, 7.
 — — the "principle" of vegetation, 4.
 Salts, alkali, effects on plants, 85.
 — — — — soil bacteria, 274.
 Sand, composition of, 102.
 — — — cultures, methods of, 356.
 — — — dune, 109.
 — — — effect in soil, 108.
 — — — — masked by organic matter, 132.
 — — — properties of, 108.
 Sandy soils, 302, 312.
 — — — characteristics of plant growth in, 312.
 — — — need no excess of calcium carbonate, 119, 336.
 — — — subject to pan, 163.
 — — — water supply in, 219.
 Scouring land in Somerset, 317.
 Seasonal effects on bacterial activity in soils, 276.
 — — — variation in activity of soil organisms, 279.
 Seed, composition of, 68, 74, 75.
 — — — effect of length of ripening period, 54.
 — — — manuring, 44.

Seed, effect of water supply, 44.

— richer in phosphorus and magnesium than in calcium and potassium, 75.

— size and weight affected by potassium supply, 70.

— — — — — slightly by nitrogen supply, 61.

— — — — — phosphate supply, 66.

Seeds, viability after long period in soil, 85

Sewage, absorption by soil, 152.

— purification; changes during, 214.

— effect of disinfecting filters, 251.

— nitrification during, 23, 190.

— nitrogen lost during, 192, 194.

— reactions during, 214.

Shade crops, 229.

Shrinkage of soils, 106, 133, 219.

Sickness in soil, 248, 287, 294.

Silica, supposed production in plants, 8.

Silicates, beneficial effect on plant growth, 15, 56, 77.

— — — — — especially with lack of phosphate, 77.

— in soil, 120, 121.

— — — Van Bemmelen's groups, 101, 103.

— Way's double, 153.

Silt, composition of, 102.

— effect in soil, 107.

— properties of, 107.

Silty clays, 312.

Sodium carbonate, toxic effects, 72, 85.

— nitrate, effect on soil tilth, 107, 116.

— salts, effect on plant growth, 72.

— — — supply of potassium salts, 151.

Soil acidity, effect on flora, 240.

— — — micro-organisms, 242.

— — — hypotheses to account for:—

Chemical: acid silicates, 110.

— aluminium salts, 112.

— exchange of bases, 112.

— hydrogen ion concentration, 113.

— organic acids, 110, 118.

Physical: preferential absorption, 110, 118.

Soil acidity, summary of present position, 117.

— analysis, 234, 322 *et seq.*, 347 *et seq.*

— colloidal properties of, 149.

— constitution of, 172 *et seq.*

— — — American hypotheses, 172.

— cultures contrasted with sand, 40, 41.

— exhaustion, 319.

— fertility, 319.

Soil fertility, theories of, 27.

— formation of, 92, 303.

— in relation to plant growth, 301.

— minute particles the "pabulum" of plants, 5.

— sampling, 324, 347.

— solution: concentration of, 125, 126.

— — — composition of, 93, 125, 127, 173.

— — — importance in soil fertility, 27.

— — — investigation *in situ* by freezing-point method, 125.

— — — methods of extraction: absorption, 125.*

— — — — — centrifugal, 124.

— — — — — displacement, 122.

— — — — — pressure, 124.

— — — osmotic pressure of, 125, 126.

— — — relation to climate, crop and season, 12', 127.

— — — — — plant growth, 173.

— — — — — soil mineral matter, 122, 125.

— — — supposed constancy of composition, 173.

— — — surveys, 322, 345.

— — — based on mechanical analysis, 343.

— — — petrogeological analysis, 346.

— — — type, characterisation of, 326.

— — — effect on plant, 45.

— — — water, 122 *et seq.*

Soils, classification of, 94.

— specially suited to certain crops or varieties, 316.

Sourness in soil, 118, 239 *et seq.*, 315.

Specific gravity of soils, 220.

— heat of soils, 229.

Spores, bacterial in soil, 216.

Stages of development of plant, effect of nitrates on, 61.

Statistical method of investigation, 18, 29.

Steppe, 314

Sterilisation of soil. See Partial sterilisation.

— — — not achieved without decomposition, 250.

Stimulation of plant growth, possibility of, 87 *et seq.*

Stones, effect in soil, 109.

Storage of soils, change during, 169.

Straw and stubble, effect on soil, 213.

— effect of nitrates, 61.

— lodging of, 62.

— — — effect of potassic fertilisers, 69.

— — — relation to grain, 62.

Strontium salts, effect on plant growth, 74.

- Subsoil, distinction from surface, 332 *et seq.*
 — effect on fertility, 332.
 — water, possible supply for plants, 221.
 Sugar, effect on soil, 201.
 Sulphates and plant growth, 76.
 Sulphocyanides, effect on plant growth, 85.
 Sulphur cycle in soil, 211.
 — dioxide, harmful effect on plant growth, 82.
 — in plants, more than formerly supposed, 76.
 Sulphuretted hydrogen, effect on plant growth, 85.
 Sulphuric acid and plant growth, 82, 268.
 — — — bacterial action in soil, 268.
 Superphosphate as fertiliser, effect on agriculture, 65.
 Surface of soil, caking of, 108.
 Suspensoids, 160.
 Swamp soils, 212. See also Paddy.
 — — air supply to plant root, 256.
 — — changes during green manuring, 213.
 — — denitrification and manuring, 210.
 — — toxic compounds in, 210, 248.
 Swelling of soil when wetted, 133.
 TCHERNOZEM, 310.
 Temperature and assimilation, 34.
 — — — enzyme action, 37.
 — — — coefficient for cell growth, 35.
 — — effect on plant growth; qualitative, 45, 46, 53.
 — — — — quantitative, 34.
 — — of soil, 229.
 — — — effect on bacterial numbers, 272, 276, 286.
 — — — lowered by clay, 106.
 — — — relation to air temperature, 231.
 — — — — bacterial activity, 272, 276.
 — — optimum conditions for growth, 53.
 — — physiological effects, 54.
 Texture of soil as affected by calcium carbonate, 117.
 — — — — organic matter, 132.
 Tilt and compound particles, 106, 171.
 — Tull on, 5.
 Topographical position and soil properties, 302.
 Torf, 136, 137.
 Toxic effects of salts, 78.
 — — — reduced by calcium ion, 78.
 Toxic effects of salts reduced by sugar, 79.
 — salts in soil, treatment of, 85, 117.
 Toxins in soil, 173, 244 *et seq.*
 Transpiration and concentration of nutrient solution, 238.
 — coefficient, 46 *et seq.*
 Tull's method of crop production, 5.
 UNDERGROUND water supply and soil fertility, 331.
 Unfavourable seasons, value of potassic fertilisers in, 71.
 "Unfree" water in soil, 220.
 VALLEYS, fertility of, 332.
 Vegetation, effect on soil formation, 93.
 — relationships; effect of soil, 301 *et seq.*
 — — — other factors, 301 *et seq.*
 — type of, effect on soil, 302.
 Vigour of plant affected by calcium, 74.
 — — — potassium supplies, 70.
 WARPING, 308, 315.
 Waste land, 327.
 Wasted fertility, 321.
 Water consumption by plant, 47.
 — — — effect of manures, 48.
 — — — — meteorological conditions, 47.
 — — — — soil conditions, 46.
 — — — — water supply, 48.
 — — — — — cultures, method of: Knop, 19.
 — — — — — Modern, 356.
 — — — — — Woodward (1699), 4.
 — — — — — evaporation from soil, 166 *et seq.*
 — — — — — Keen's equation, 167.
 — — — — — holding capacity of soil, 223.
 — — in soil, coefficients, relations between various, 226.
 — — — — — continuity of state, 224.
 — — — — — determination of, 348.
 — — — — — supposed various states, 166.
 — — — — — volume of, 220.
 — — — — — retention by soil, 166.
 — — — — — magnitude of forces determining, 225.
 — — — — — supply and interpretation of mechanical analysis, 329.
 — — — — — effect on leaves, 44.
 — — — — — plant growth; qualitative, 43.
 — — — — — — quantitative, 38.
 — — — — — roots, 44.
 — — — — — seed formation, 44.
 — — — — — influence in determining value of manures, 64.
 — — — — — in soil, 218, 301.

— — — — effect on bacterial activity,
272, 276.

— — — — — numbers, 272,
276, 286.

- — — — movement of, 218 *et seq.*
- — utilisation of food, 38.

— the "principle" of vegetation, 3.

— vapour, absorption by soil, 170.

Waxlike constituents of soil, 144.

Weathering of soil, 93, 99.
Weeds, checked by heavy crop, 55.

Wilting coefficient, 221.

— phenomena of, 221.

— point, 168, 221.

Woodland soils, nitrates in, 146.

— — nitrification in, 146.

— — nitrogen content, 55.

ZEOLITES, reactions of, 103.

— supposed presence in soil, 109.

Zinc salts, beneficial in small quantities,
56, 85.

— — harmful in larger amounts, 85.

